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THE EFFECT OF AN ELECTROSTATIC FIELD ON THE CONDENSATION OF VAPOR

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RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Project No. 3084, Task No. 308404

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300 - April 1964 - 162 - 32-629

FOREWORD

This report was prepared by the Air Force Aero Propulsion Laboratory of the Research and Technology Division with Henry R. Velkoff and John H. Miller acting as project engineers. The work reported herein was accomplished under Project Number 3084, entitled "Propulsion Fluid and Heat Transfer Subsystems."

The work presented herein is a continuation of a sequence of programs exploring the basic nature and the practical applications of the interactions of electrostatic fields with fluids. This report covers research conducted during the period September 1962 to August 1963.

The authors wish to express their appreciation to Mr. Robert Schelenz for his fine work in fabricating, checking out, and running the test equipment used in the conduct of the work.

Specific mention must be made of the work of Dr. Harry Y. Choi of Tufts University, in the area of the effects of electric fields on boiling and condensation. Although the work reported herein was conceived and accomplished independently of Dr. Choi, the authors are indebted to him for the discussions and his encouragement during the course of the work.

ABSTRACT

This experimental program was conducted to determine whether electrostatic fields could be applied effectively to increase the heat transfer coefficient in the condensation of vapor. A series of tests using several types of electrodes and various field strengths was conducted to study the effects of various electrostatic actions on the condensation process. In these tests, Freon-113 was vaporized in a tank and condensed on a cooled copper plate. Results of these tests indicate that large increases in heat transfer coefficient can be realized by applying an electrostatic field with a screen electrode placed parallel to a cooled copper plate. The increases were controllable and readily reproduced.

This report has been reviewed and is approved.

ROBERT E. SUPP
Assistant Chief
Aerospace Power Division

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LIST OF SYMBOLS

h_m = the average coefficient of heat transfer, taken for the whole condensing surface, $\frac{\text{Btu}}{\text{ft}^2 \text{ hr } ^\circ\text{F}} \frac{\text{ft}}{}$

g = acceleration of gravity, 4.18×10^8 ft hr^{-2}

λ = the latent heat of condensation, Btu per pound

L = the height of a vertical wall, ft

ρ = the density of the condensate at its average temperature, lb ft^{-3}

k = the thermal conductivity of the condensate at its average temperature, $\frac{\text{Btu}}{\text{ft}^2 \text{ hr } ^\circ\text{F}} \frac{\text{ft}}{}$

μ = the viscosity of the condensate at its average temperature, $\frac{\text{lb}}{\text{ft hr}}$

ΔT = the temperature difference across the condensed film, °F

P = pressure, neutrons/meter^2

ϵ = permittivity, farads/meter

E = electric field strength, volts/meter

INTRODUCTION

Condensation of vapors has become an important element in several new concepts for aerospace propulsion. In these concepts it is necessary to chill and condense large quantities of air, nitrogen, or oxygen. The weights of the propulsion systems must be kept to a minimum and any excess volume would exact penalties in flight vehicle performance at high operating speeds. The condensers in these concepts may handle hundreds of pounds of condensate per second and consequently a high order of skill must be exercised in design and fabrication if the required flight characteristics are to be met. Any improvements in condenser performance, consequently, would be reflected in the increased payload capabilities of the flight vehicle.

The controlling factor in condenser effectiveness is the magnitude of the heat transfer coefficient. If this coefficient can be increased, then the net size and weight of the condenser can be reduced. It has been found in the past that substantial increases in heat transfer coefficients are difficult to attain.

It appeared, however, that proper application of electrostatic fields could lead to substantial increases in the condensation heat transfer coefficient. Based upon a broad study of the possible interactions between electrostatic fields and fluids reported in Reference 1, several possible actions could be used to influence the fundamental mechanisms involved in the condensation of vapors. An exploratory program was undertaken, therefore, to investigate these possible actions on the condensation of vapors. In the investigation, Freon-113 was vaporized and then condensed on a cooled copper plate in the presence of selected electrostatic fields.

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PRELIMINARY CONSIDERATIONS

Since the primary resistance to heat transfer in the condensation of vapors is the film of liquid that forms on the cooled surface, an effective means for increasing heat transfer must provide some means of eliminating or modifying this film. Past work has been focused on techniques which mechanically remove the condensate, provide special surfaces which utilize surface tension forces, or promote dropwise condensation (References 2 and 3). It has been found extremely difficult to employ these schemes in practical condensers to obtain higher heat transfer coefficients. Likewise, any attempt to utilize electrostatic effects must recognize this controlling nature of the film.

The interactions of electrostatic fields with fluids offer several physical mechanisms which could possibly influence the condensation process. Proper application of electrostatic fields could induce:

1. Nucleation sites for vapor condensation by providing ions in the vapor space near the condensing surface, and thus cause "induced heterogeneous nucleation".

2. An electrostatic force to drive the small clusters of ions or charged droplets to the cooled surface. Charge motion and electric wind could be active simultaneously.

3. Nonuniform thermal or electrical-field body forces to precipitate vapor onto regions of intense field. This technique would probably be applicable to polar fluids.

4. Destablization of the condensate film by the action of the surface charge created by the field and the surface tension at the film-vapor interface.

5. Electrostatic pumping of the liquid from the film to reduce the thickness of the film.

6. Internal mixing of the film itself, resulting in some type of turbulent condensation.

Actions 1 and 2 can occur continuously only if the vapor is subcooled, or if some fine drops or spray exist in the vapor due to external causes. The other actions can occur continuously without subcooling or without the presence of drops.

In June 1962, an experimental program was devised to determine whether some of these actions were active in the condensation process and whether any was potentially useful. Since the mechanisms for heat transfer and mass transfer are similar, it was decided that the configuration for conducting the condensation tests should be similar to that used for the free-convection tests reported in Reference 4. The preliminary test setup for the heat transfer tests is shown in Figure 1. Freon-113 would be vaporized and passed into a plexiglas container. A cooled vertical copper plate would be used as the condenser, and an electrode placed directly in front of the plate would provide the electrical field. The electrodes were to be single wire and rod electrodes, as were used for the free-convection tests (Figure 7, Reference 4). The effectiveness of the system in removing the film would be measured by the amount of liquid collected as it dripped off the bottom of the plate.

Before the project was approved, however, the proposed tests were discussed with Dr. Harry Y. Choi of Tufts University, who had done some preliminary work on condensation with electrical fields. In those tests, he said, a good deal of the film left the plate

in the form of a spray, and this spray could not be readily collected in the container at the bottom of the plate. His results showed heat transfer was increased on the order of 50 percent. Based upon these discussions, we changed the configuration of the test equipment since the configuration shown in Figure 1 apparently could not give accurate measurements of the amount of condensate formed. The program was approved in September 1962 and the investigation was conducted as described in the following sections.

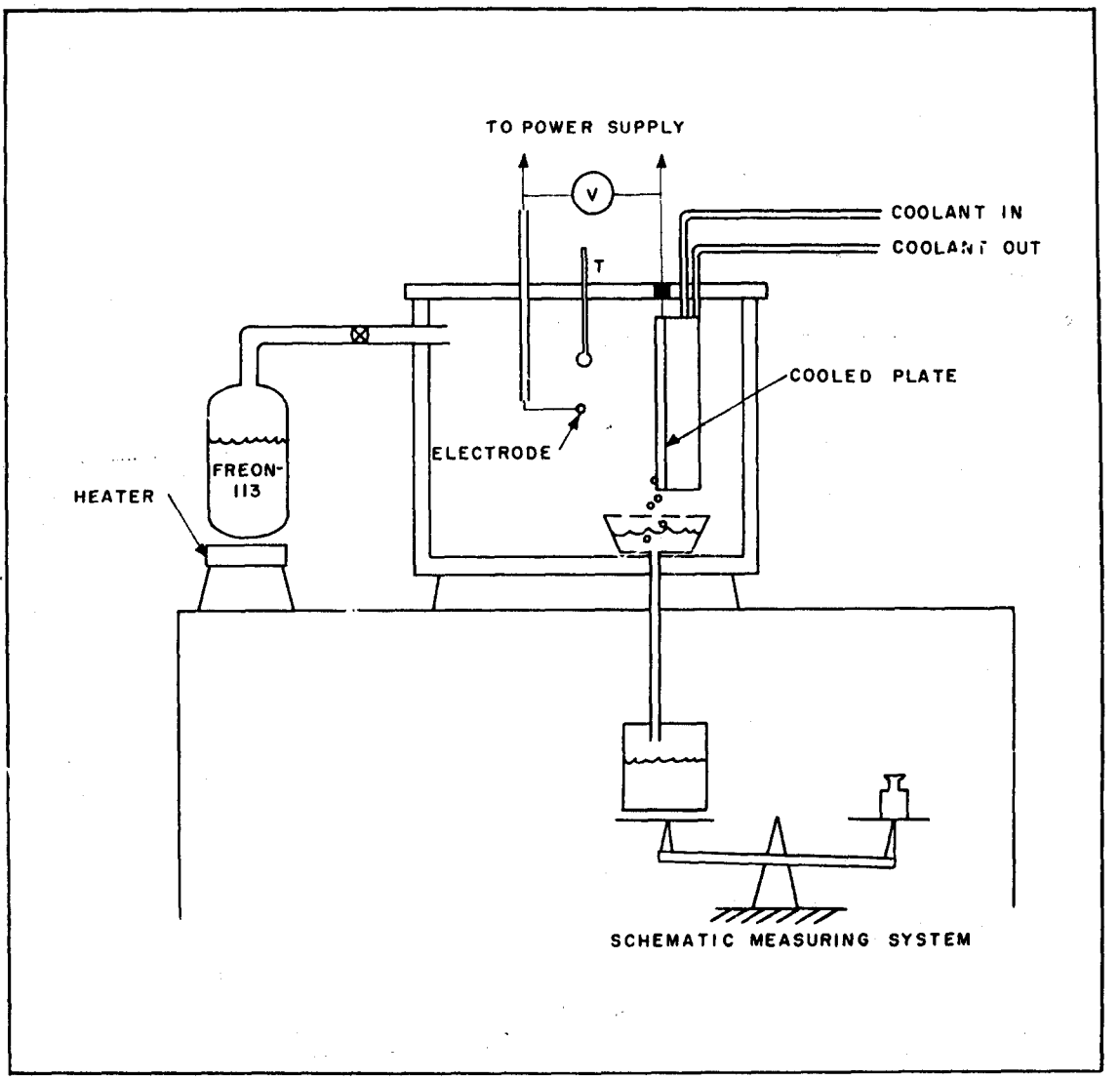

Figure 1. Original Concept of Experimental Apparatus

EXPERIMENTAL INVESTIGATION

A schematic of the test configuration used in these experiments is shown in Figure 2. The container is a plexiglas tank with a copper plate mounted on one side to serve as the condenser. Electric heaters are installed at the bottom of the tank to heat and evaporate the fluid. Freon-113 was used as the working fluid in all of these experiments; enough of the fluid was poured into the tank to cover the heaters. As the Freon-113 condensed during the tests, it was permitted to drop back into the fluid at the bottom of the tank. No attempt was made to collect and measure the condensate, as had been planned originally, since Choi's experiments had indicated it would be difficult to measure the amount of condensate leaving the plate.

In this test configuration, we determined the heat absorbed by the plate by measuring the flow rate and temperature rise of the coolant. Nine thermocouples were mounted in the copper plate to measure plate temperature, and mercury thermometers were mounted in the tank near the front of the plate to measure vapor temperature. Pressure in the tank was monitored carefully to maintain a preset value during all tests.

Electrodes of different types and designs were inserted in the tank to provide the electrostatic field. Designs included single wire, oval wire, wire grid, aluminum plate, and 5- and 15-mesh screen electrodes (as shown in the Appendix, Figure 32). The tank was equipped with a removable top to facilitate changing the electrodes for the different tests.

The test sequence was established to determine the effects of the following on the condensation of vapor:

1. Charging the vapor with an intense corona current about a fine wire electrode and the actions of the charge deposited on the surface of the condensate.

2. Corona wind on the rate of condensation.

3. Forced convection (fan-induced wind) on the rate of condensation, for comparison with the results for electrostatic fields.

4. A uniform electric field on the stability of the condensate surface.

Considerable difficulty was encountered in locating the secreen electrodes precisely in front of the cooled plate and exactly parallel to it. Some of these difficulties arose from problems encountered in fabrication of the screen electrodes and some from the slight warping that occurred due to electrostatic attraction when high fields were applied.

Techniques used in conducting the tests are described in the Appendix.

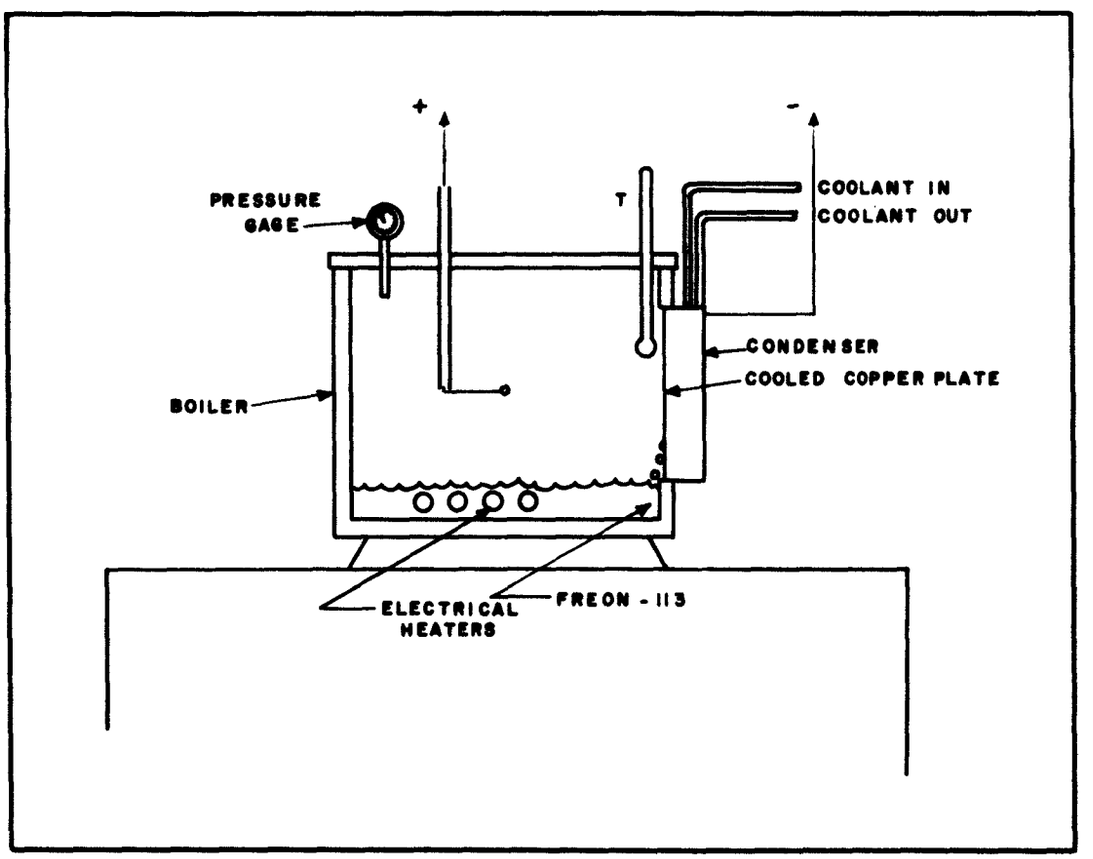

Figure 2. Schematic of Experimental Apparatus as Revised

TEST RESULTS

FINE WIRE ELECTRODE

The first test sequence with the fine wire electrode (0.004-inch diameter) was conducted without any applied field to provide reference data on the condensation of Freon-113 vapor. The temperatures of the vapor and of the cooled plate were measured, and the difference in temperatures was used to determine the average heat transfer coefficient. As is usually done in heat transfer correlation with condensed vapors, the temperature of the vapor adjacent to the film was used to determine the temperature difference rather than the temperature of the film surface itself. These values were compared with values obtained from the theoretical Nusselt equation for laminar film condensation on a flat vertical plate:

$$h_m = 0.943 \left[\frac{g\lambda}{L} \frac{\rho^2 k^3}{\mu}\right]^{\frac{1}{4}} \left(\frac{1}{\Delta T}\right)^{\frac{1}{4}} \quad (1)$$

The theoretical and experimental values (with no electrode) have been plotted in Figure 3. The experimental data agree quite well with theoretical values, although considerable scatter does exist. Similar data measured with a 0.004-inch diameter corona wire placed horizontally in front of the plate but with no applied field are also plotted in Figure 3. A comparison of these data shows that the presence of the wire, in itself, has little effect on the values of h_m.

The next series of tests was designed to determine the effects of applying an electrical field with the 0.004-inch corona wire. The wire was located one inch from the plate and a corona current of 1000 microamperes was applied. The data showed both increased and decreased values of h_m. The extreme amount of scatter in these values is apparent in Figure 4. The corona current was then reduced to 300 microamperes. Values of h_m increased slightly above those for no applied field (Figure 3). With a corona current of 100 microamperes, data was consistent and values for h_m were increased by approximately 25 percent, as shown in Figure 5. Results obtained with the wire 2 inches from the plate and a corona current of 70 microamperes are plotted in Figure 6. Values for a vertical wire 1 inch from the plate and a corona current of 100 microamperes are shown in Figure 7. The results show that these variations affected the values very little. Results obtained with a grid of 0.004-inch wires placed horizontally 1 inch from the plate are plotted in Figure 8. The values for h_m increased at small differences in temperature, but the increase dropped sharply at higher values of ΔT.

A comparison of plots for this sequence of tests (Figures 3 through 8) showed that values of h_m improved only slightly with applied field when the fine wire electrode was used. The net improvement in h_m at higher values of current, considering the power required to accomplish the corona charging action, is so small as to be considered negligible. These tests revealed some actions of the corona charge on the condensation process, however, that are of interest.

With no applied field and low ΔT, the cooled plate was entirely covered with a film of condensate having a smooth and shiny surface (laminar film). When values of ΔT were increased, however, a region of turbulence developed in the film at the bottom of the plate. As ΔT was increased still further, the amount of turbulence in the film increased and appeared higher on the plate. When an electrical field was applied with a laminar film,

noticeable effects occurred in the film. At a specific value of electrical field, the smooth surface took on a slightly wavy appearance. As the field strength was increased and a corona current began to flow, the entire surface of the film became turbulent. The condensate formed into regularly spaced rivulets which carried off most of the condensate. At currents near 1000 microamperes, strong electric wind effects produced an almost dry region at the centerline directly in front of the wire and ridges of condensate above and below. This corona wind could be expected to disrupt the condensation mechanism and produce erratic values, such as appear in Figure 4. A certain value of field had to be reached, however, before the effects were noticeable on the condensation process.

PARALLEL PLATE TESTS

The second series of tests was designed to determine whether the electrostatic field effects from parallel plate geometry would produce useful instabilities in the surface of the film. Fringing effects of the field occur with simple parallel plate geometry, but the added complexity of using Rogowski electrodes (Ref. 5) was not believed warranted in these exploratory tests. The plate was constructed of 15-mesh screen, rather than of sheet metal, to provide a less restricted path for the vapor to reach the cooled plate. The first test with the 15-mesh screen electrode was conducted with no applied field to provide reference values. Next, a field of 50 KV was applied. The values obtained are plotted in Figure 9. The increase in h_m was approximately 55 percent, yet the current was much lower than that occurring with the single wire electrodes in the previous tests.

The tests with the 15-mesh screen showed that this type electrode produced decided improvements in the heat transfer coefficient. A new electrode of 5-mesh screen was constructed, therefore, and installed at a distance of 1/4 inch from the cooled plate. Values of h_m were measured with no field, and applied fields of 10, 20, and 30 KV. These values are plotted in Figure 10. The values for h_m with a field of 30 KV are much better than those obtained with a single wire electrode at much higher applied voltages.

An interesting phenomenon was observed during the conduct of the tests with the screen electrodes. As the electrical field was applied, a value of voltage was reached at which the entire condensation process changed radically. The surface of the film on the cooled plate became wavy, and the liquid appeared to be pumped off the bottom of the plate in very fine jets at high speed. The most unusual aspect of the phenomenon occurred at the screen grid. All the wires of the screen electrode became entirely covered with liquid, and this liquid appeared to be attracted toward the cooled plate in fine points. At the bottom of the grid, liquid was pumped off the electrode in the same manner as it was pumped off the cooled plate. As much of the liquid condensate spray appeared to come from the screen grid as from the plate.

Further tests were devised to investigate and verify the actions of fields on the condensation process. The first of this series of tests was designed to determine whether actions similar to those observed with the single corona wire or with the screen grid could be achieved by blowing the vapor against the plate. It was recognized that the corona wind, which occurred at high values of applied current with the fine wire, could be simulated by a fan. Runs were made with a fan blowing directly on the plate under three conditions: with no screen in place; with the screen in place but no applied field; and with an applied field. Results of these tests are plotted in Figure 11. A comparison of these values with those of Figure 10 shows that the fan has little effect on the condensation process, with or without an applied electrical field, and may even reduce the heat transfer coefficient slightly.

In the next series of tests, a flat aluminum plate was used as the electrode to obviate the effects of the local electrostatic fields existing with a screen. Unfortunately, with a solid sheet of aluminum installed in front of the condenser surface, the only vapor reaching the condenser would be that which passed around the perimeter. These tests, therefore, were conducted with the electrode at several different spacings from the condenser to provide various passage areas for the vapor. Data are plotted in Figure 12 for a 1/4-inch spacing, in Figure 13 for a 1/2-inch spacing, and in Figure 14 for a 1-inch spacing. Values obtained in these tests showed that a field applied with a solid plate electrode improved h_m somewhat, but the increase was not as great as with the screen electrodes. The difference was believed to be due to the restricted vapor passage to the condenser. We decided, therefore, that although the nature of the screen electrode causes localized differences in the electrical field, it offers more potential for increasing the heat transfer coefficient.

LOW TEMPERATURE TESTS

Next, efforts were made to determine the effectiveness of the electrostatic field with a greater range of temperature difference. Tests run with the screen at a distance of 1/4 inch from the condenser surface provided the data plotted in Figure 15. To obtain greater temperature differences, we revised the test setup, as described in the Appendix. Tests were again conducted with the 5-mesh screen electrode at a spacing of 1/4 inch. Results, which are plotted in Figure 16, show an increase in h_m that is much less than was anticipated from an extrapolation of data from previous tests. During these low-temperature tests, however, we had noticed a localized electrical discharge occurring at the lower edge of the plate, and we believed that such a discharge could adversely affect the condensation process. The plexiglas of the tank around the lower edge of the plate was discolored, and sparking was noted from this area. The affected area was cleaned, polished, and coated in an attempt to prevent this discharge, but these efforts failed. We installed a new plexiglas container, therefore, to correct this electrical breakdown.

Tests were conducted with the revised test setup at values of ΔT ranging from 2.6°F to 33°F. No electrical discharge was noted. Values of h_m obtained in these tests are plotted in Figure 17, together with values from some previous tests for comparison. The heat transfer coefficient with applied field is increased approximately 2-1/2 times over that without an applied field. In addition, values lie on a line approximately parallel to, but displaced above, the theoretical values for laminar film condensation (Nusselt equation).

A series of tests was then conducted using the 5-mesh screen electrode at various spacings and with various values of electrical field strength. Results of these tests are plotted in Figures 18 through 22. In general, the plots show that a substantial increase in h_m is possible with applied field.

A further test was conducted using a wire oval electrode (Figure 31) mounted horizontally 1/2 inch from the centerline of the cooled plate. Results of these tests are plotted in Figure 23. A comparison of these values with values for no field (Figure 3) indicate that h_m is essentially unchanged with this type electrode.

The variation in heat transfer coefficient with field strength for the 5-mesh screen electrode is shown in Figure 24. Curves are plotted for $\Delta T = 4°F$ and $\Delta T = 9°F$. These curves show that a certain value of field strength must be reached before the electrostatic phenomena become active on the condensation process. The minimum value for the conditions encountered in these tests was approximately 25 kilovolts/cm.

The amount of heat transferred (Btu/hr) is plotted in Figure 25 against the electrical power input to the electrode while maintaining a ΔT of 9°F. The large amount of scatter in the data prevents any definite conclusions from being drawn, but the data shows a general trend of increasing values at higher currents.

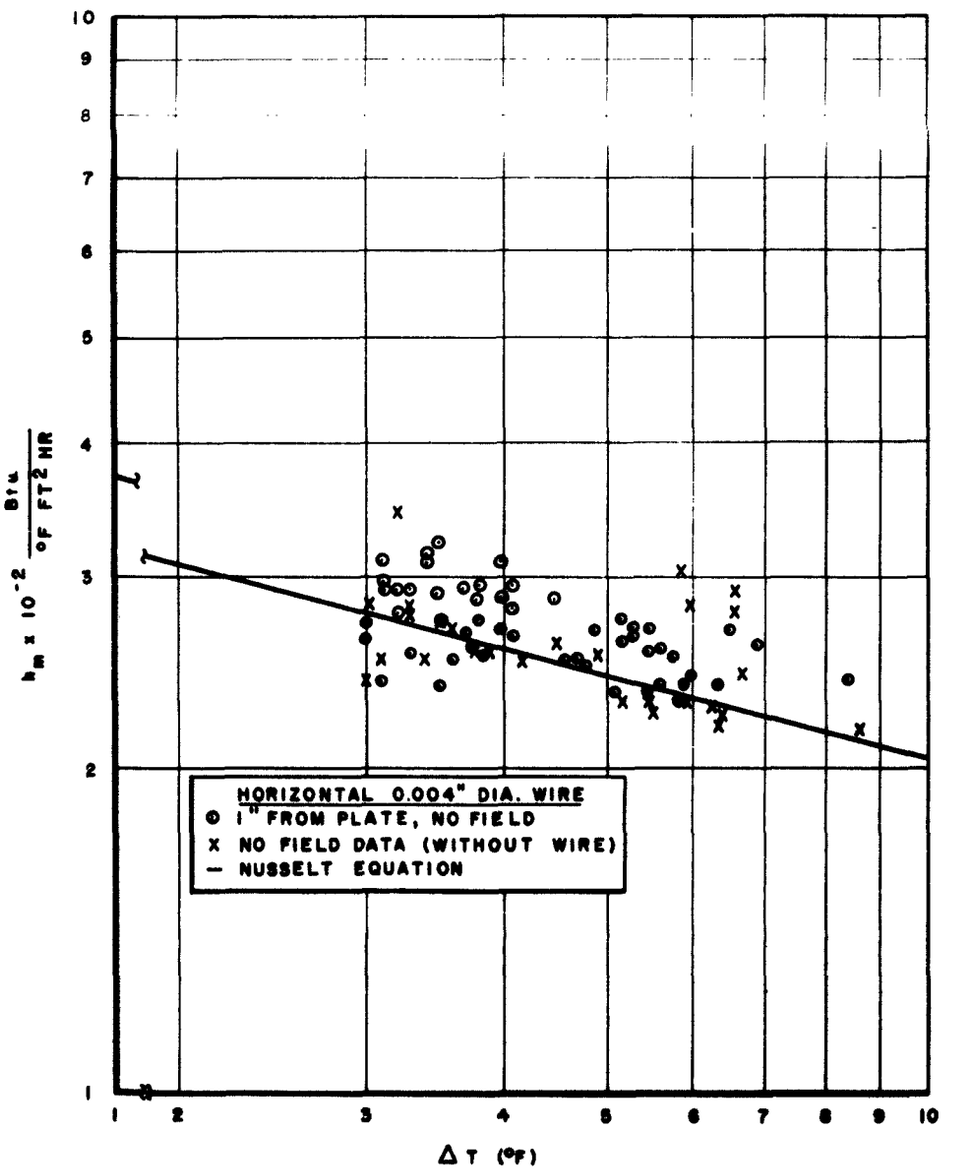

Figure 3. Theoretical and Experimental Values with No Applied Field

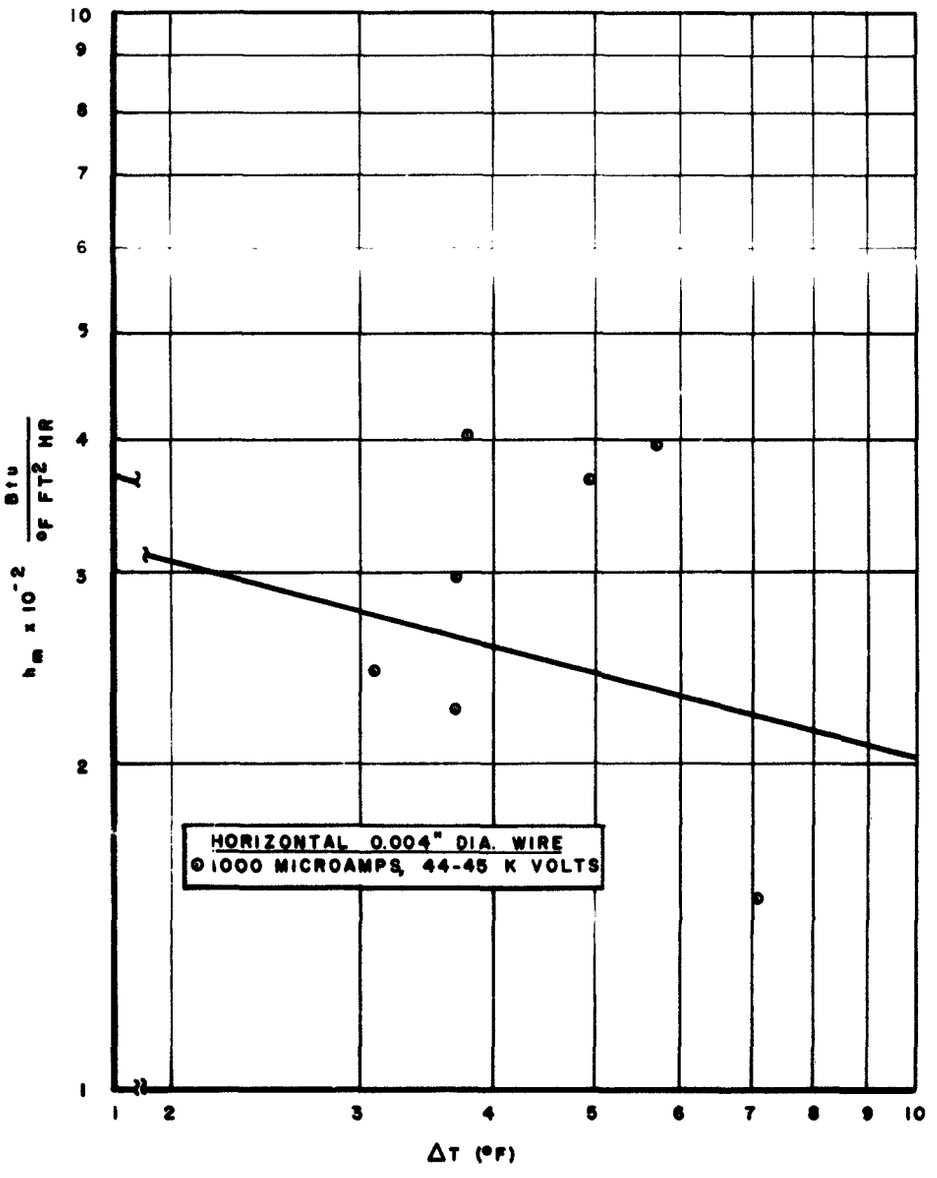

Figure 4. Effects of Corona Current with Wire 1/2 Inch from Plate

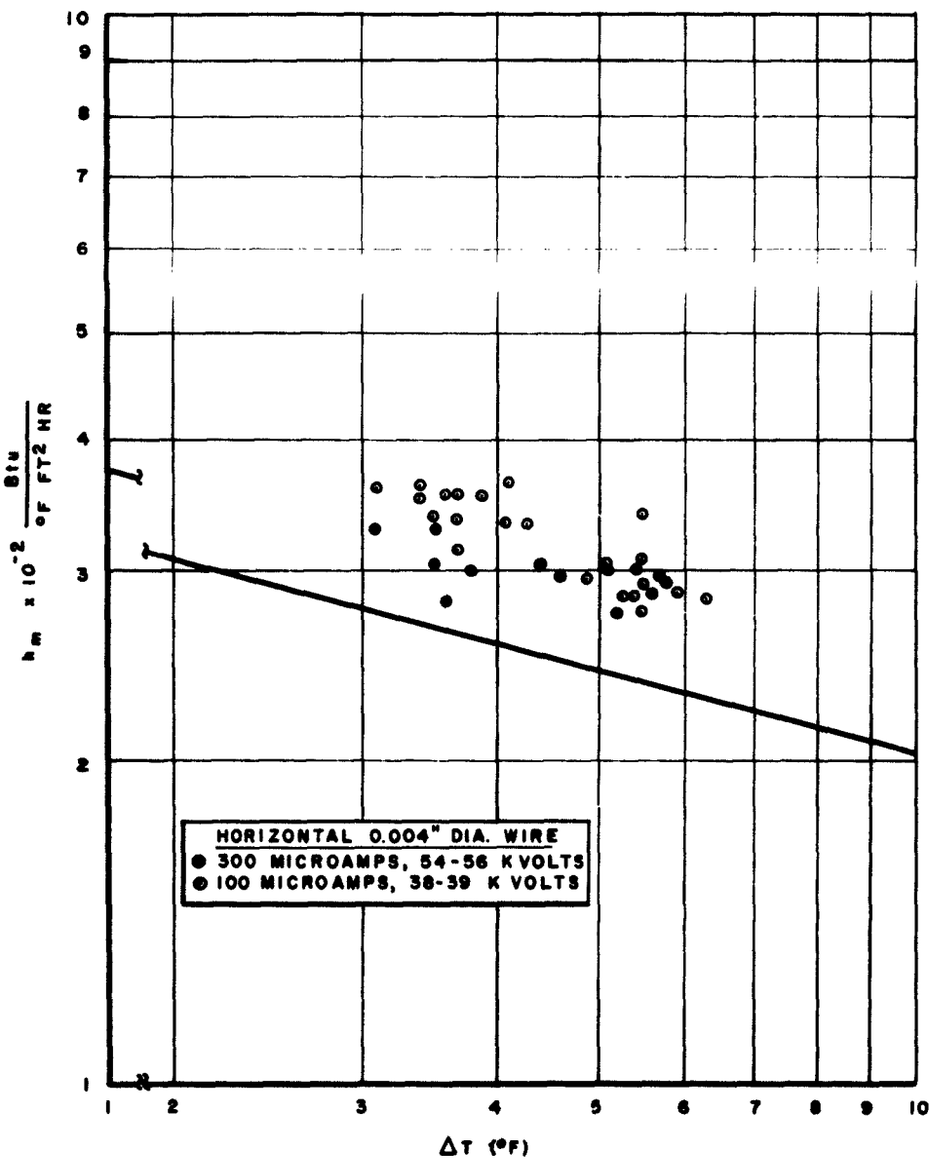

Figure 5. Effects of Corona Current with Wire 1 Inch from Plate

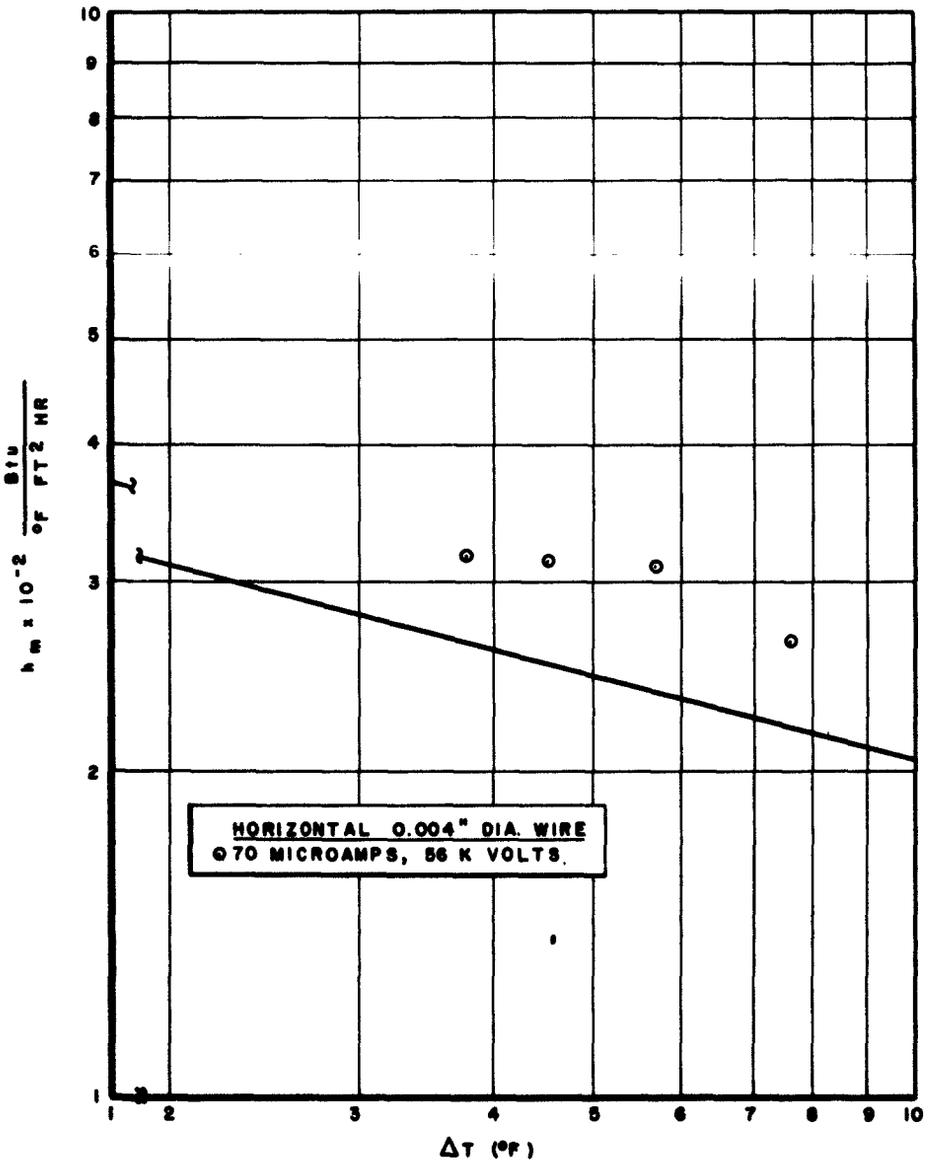

Figure 6. Effects of Corona Current with Wire 2 Inches from Plate

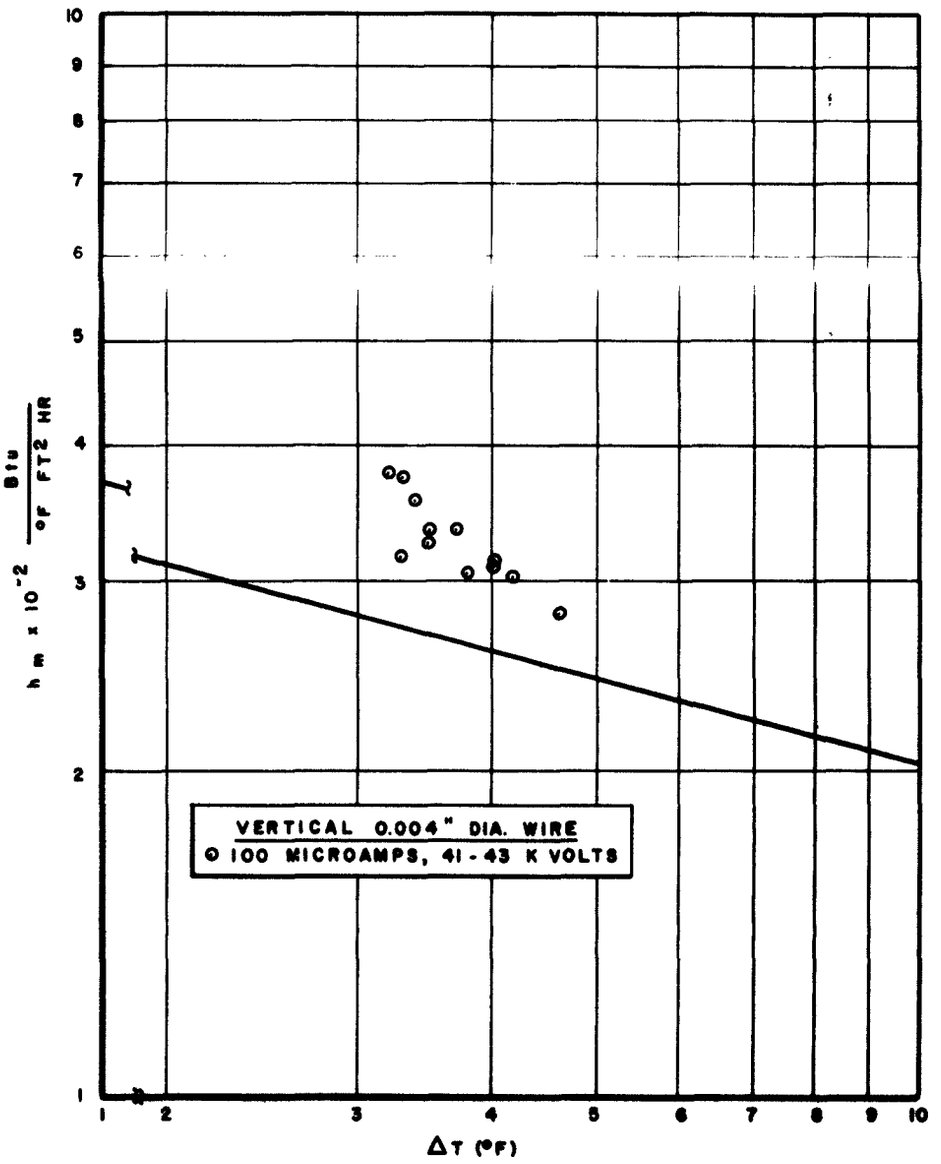

Figure 7. Effects of Corona Current with Vertical Wire 1 Inch from Plate

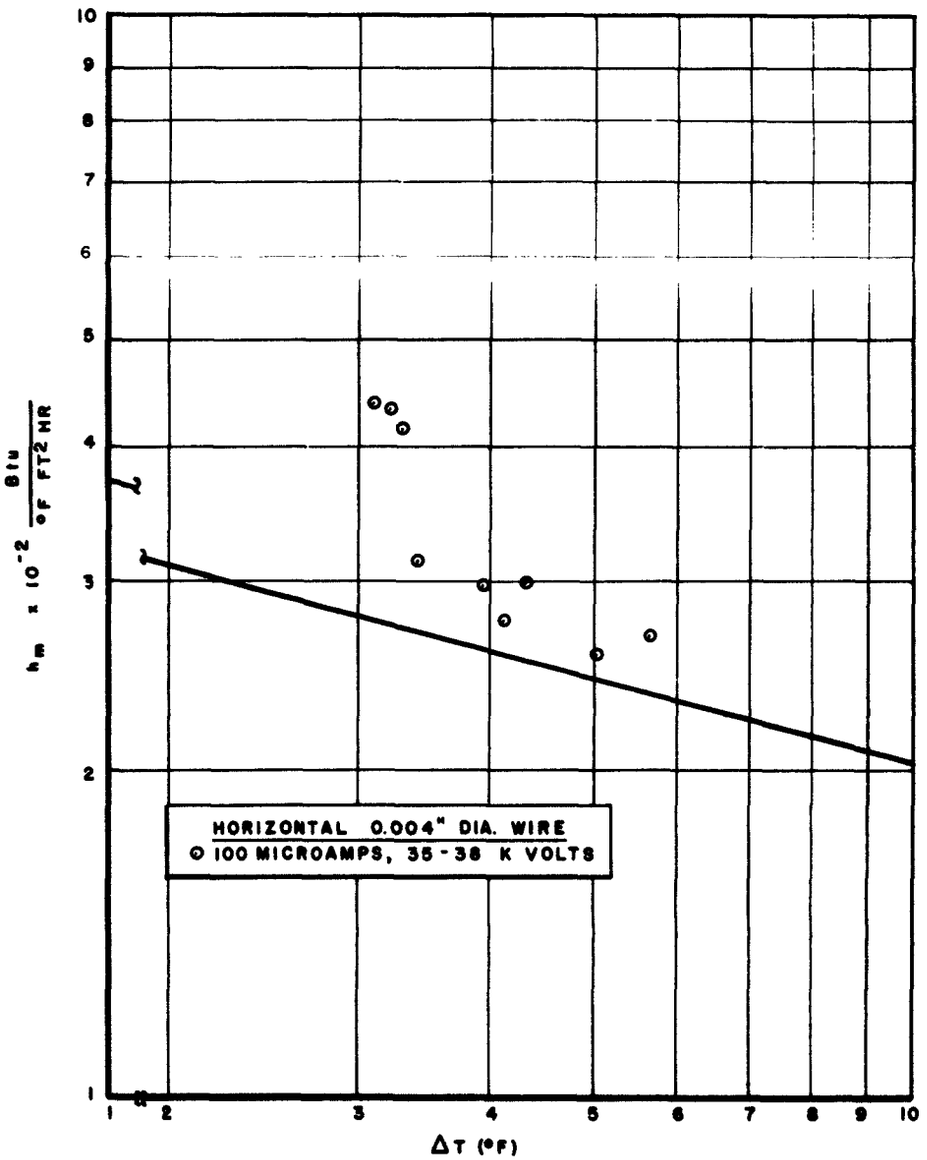

Figure 8. Effects of Corona Current with Wire Grid 1 Inch from Plate

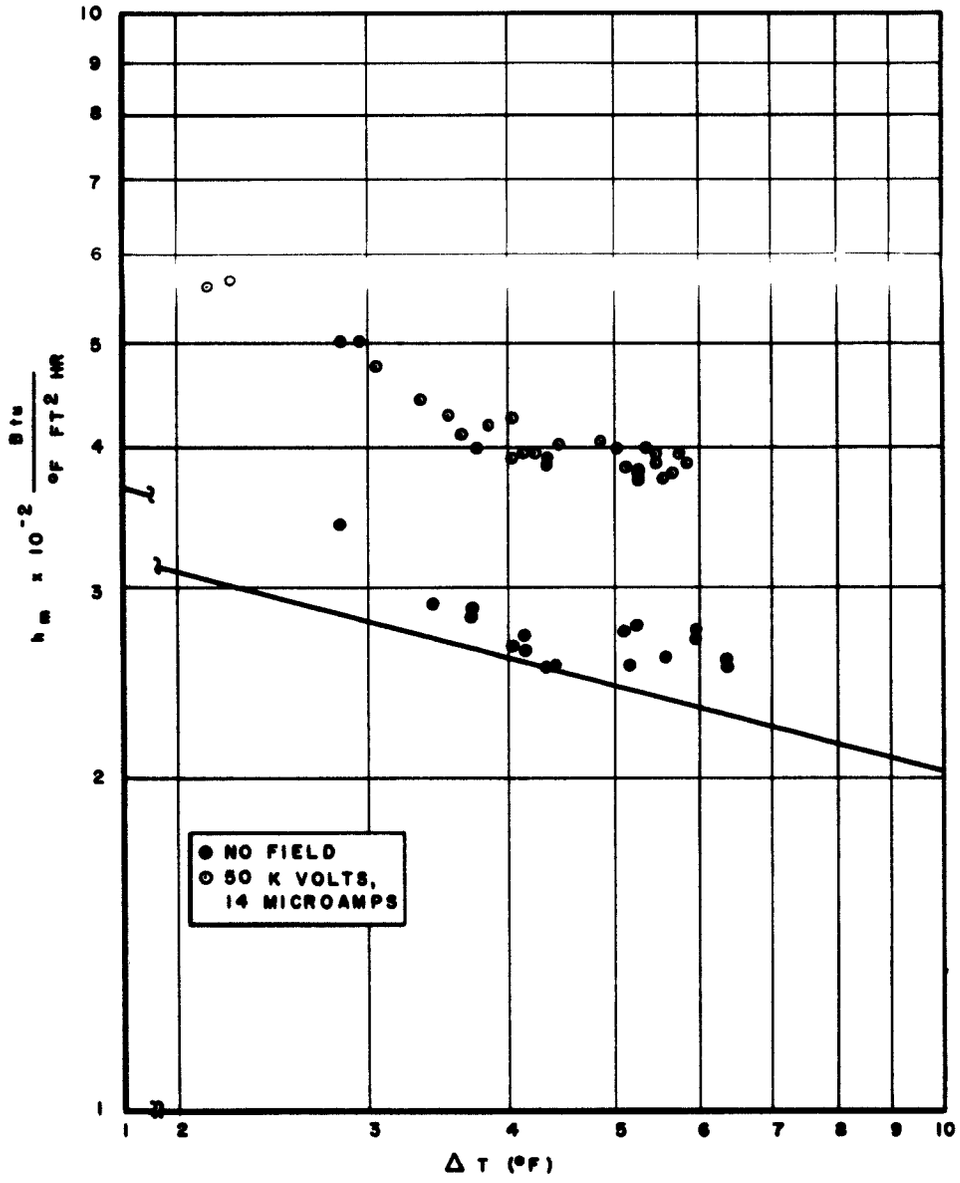

Figure 9. Effects of Parallel Plate Geometry with 15-Mesh Screen 1 Inch from Plate

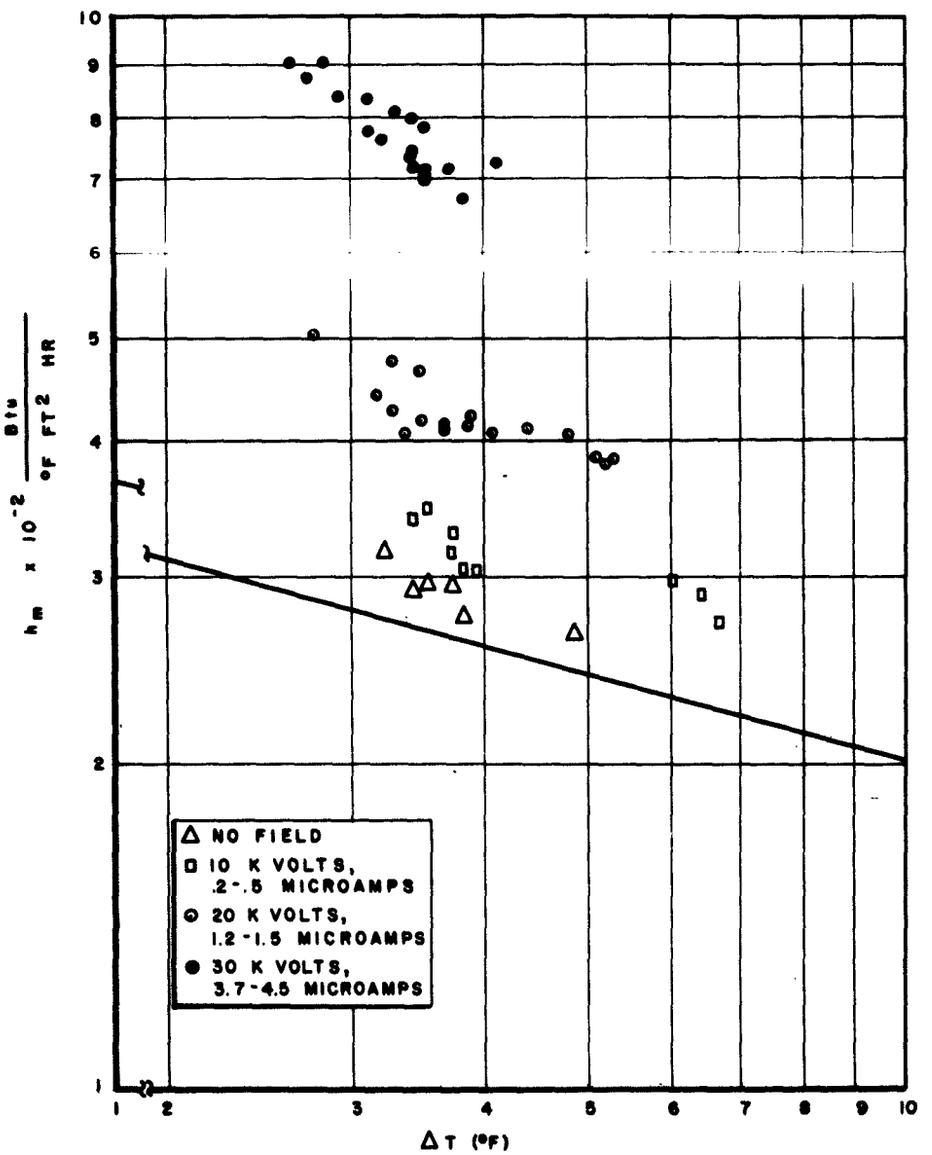

Figure 10. Effects of Parallel Plate Geometry with 5-Mesh Screen 1/4 Inch from Plate

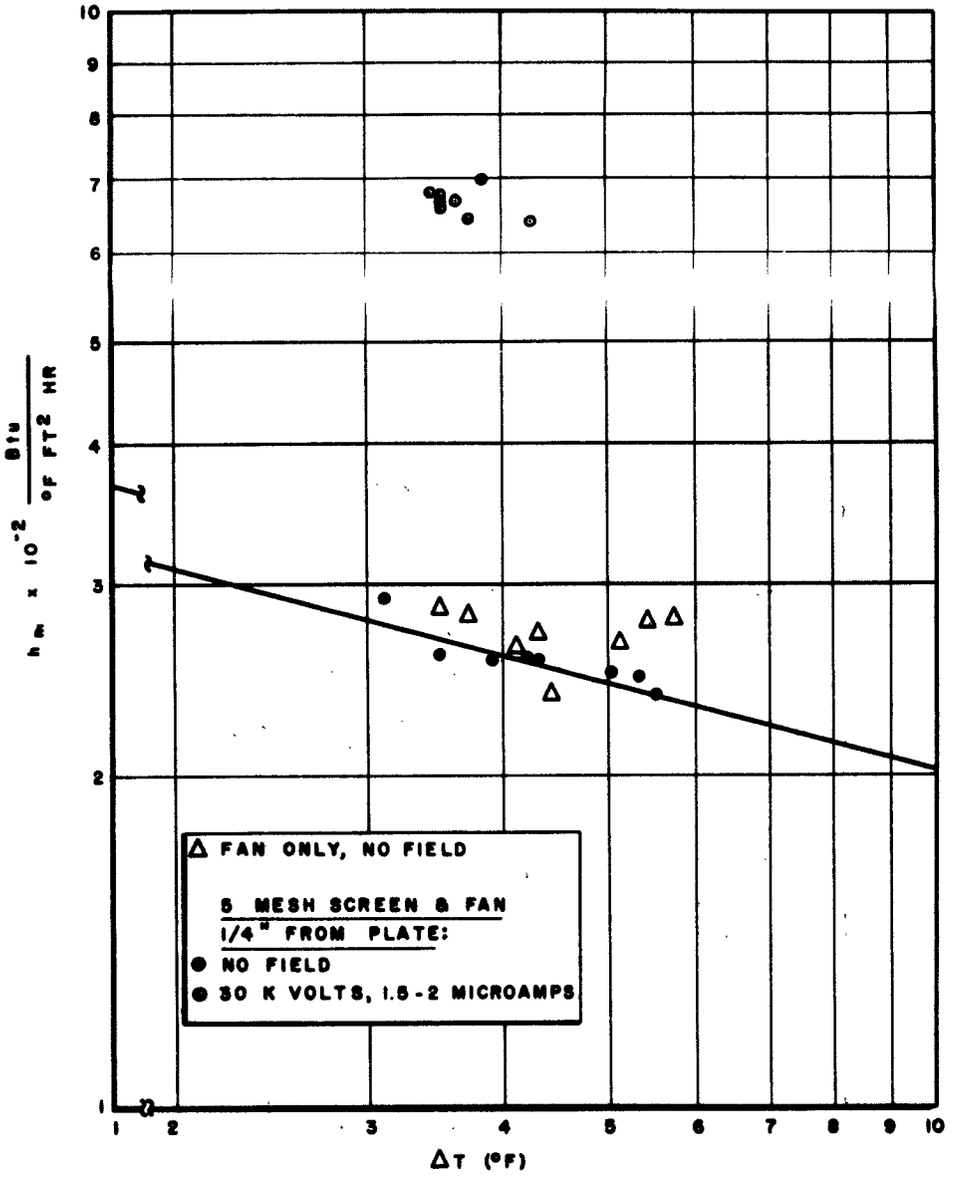

Figure 11. Effects of Forced Convection and Electrostatic Field

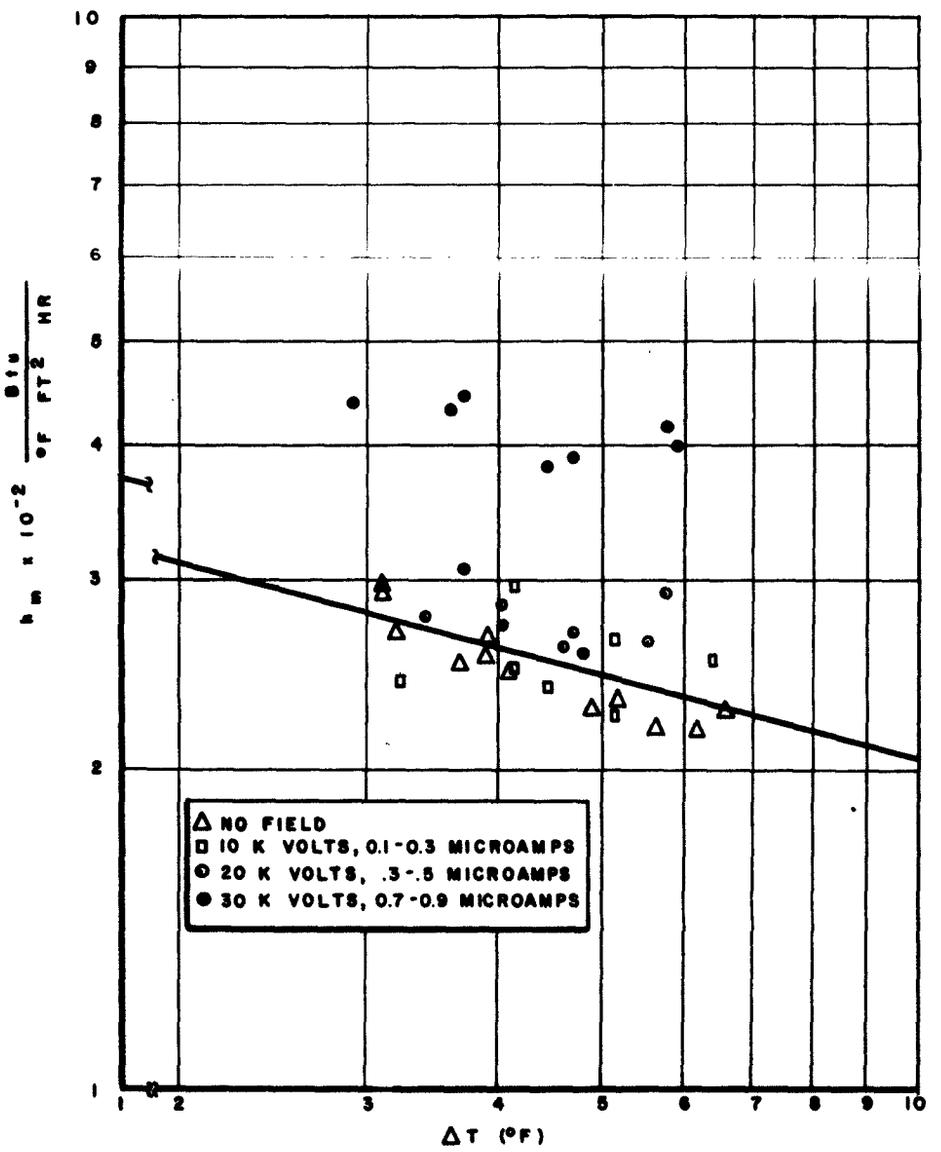

Figure 12. Effects of Electrostatic Field with Aluminum Plate 1/4 Inch from Plate

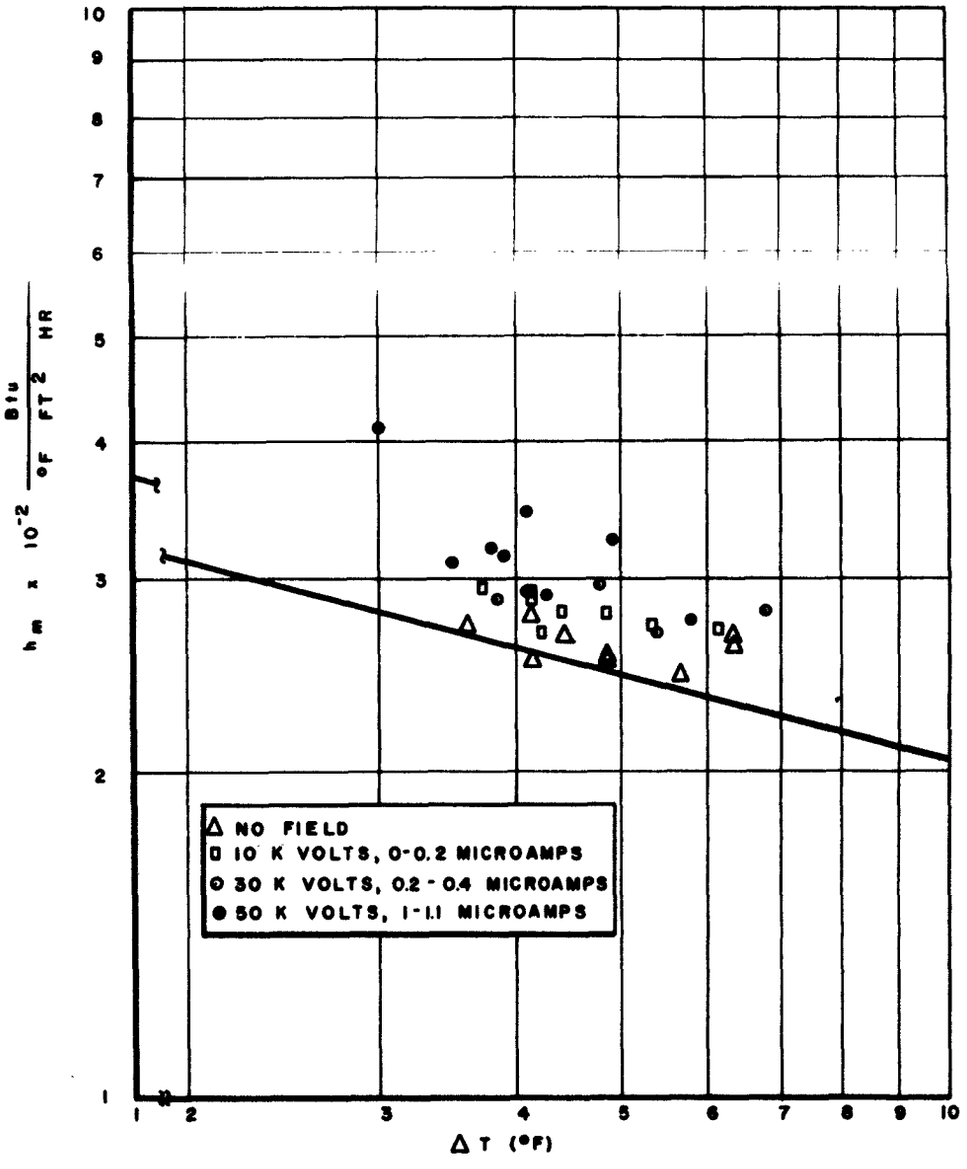

Figure 13. Effects of Electrostatic Field with Aluminum Plate 1/2 Inch from Plate

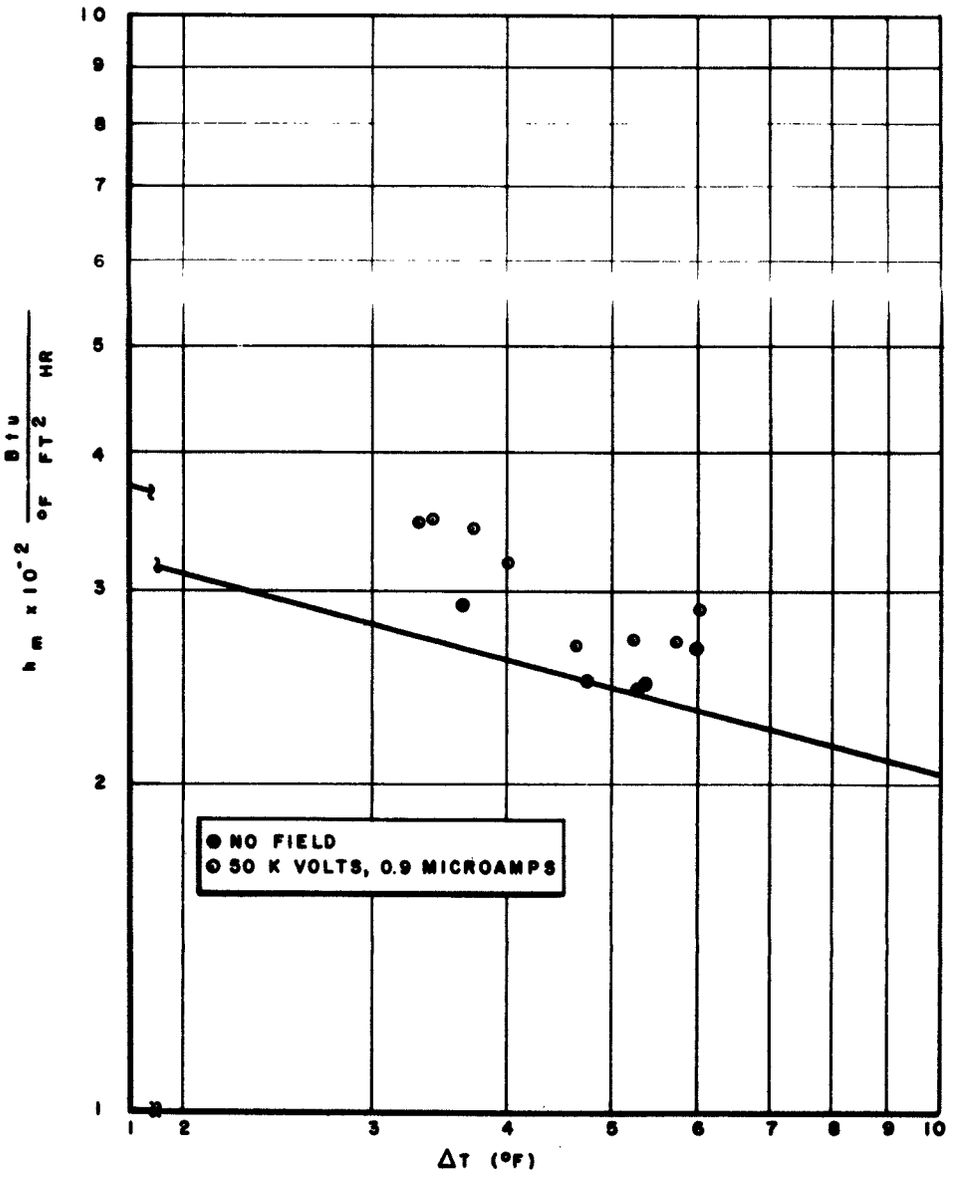

Figure 14. Effects of Electrostatic Field with Aluminum Plate 1 Inch from Plate

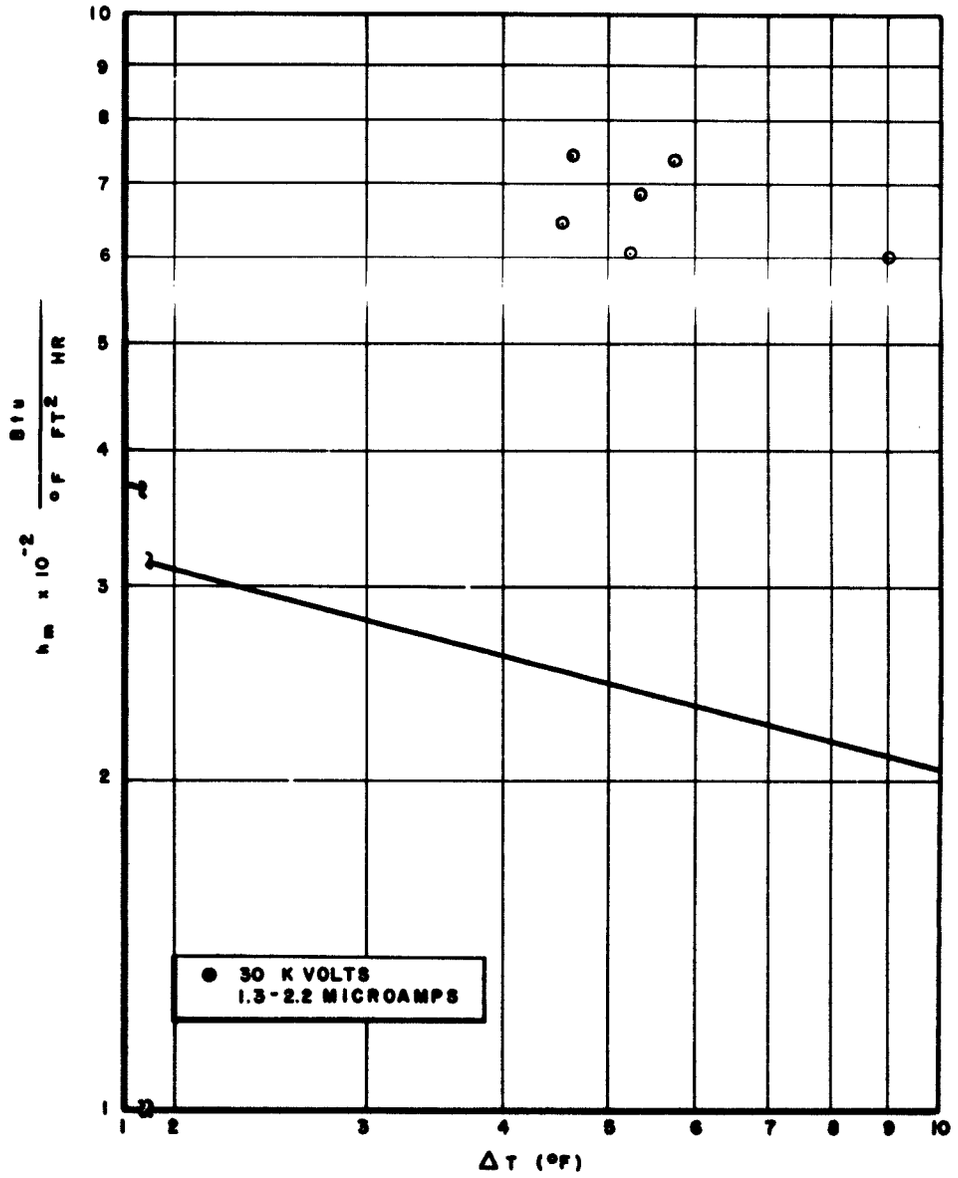

Figure 15. Effects of Electrostatic Field with 5-Mesh Screen, at Lower Values of ΔT, 1/4 Inch from Plate

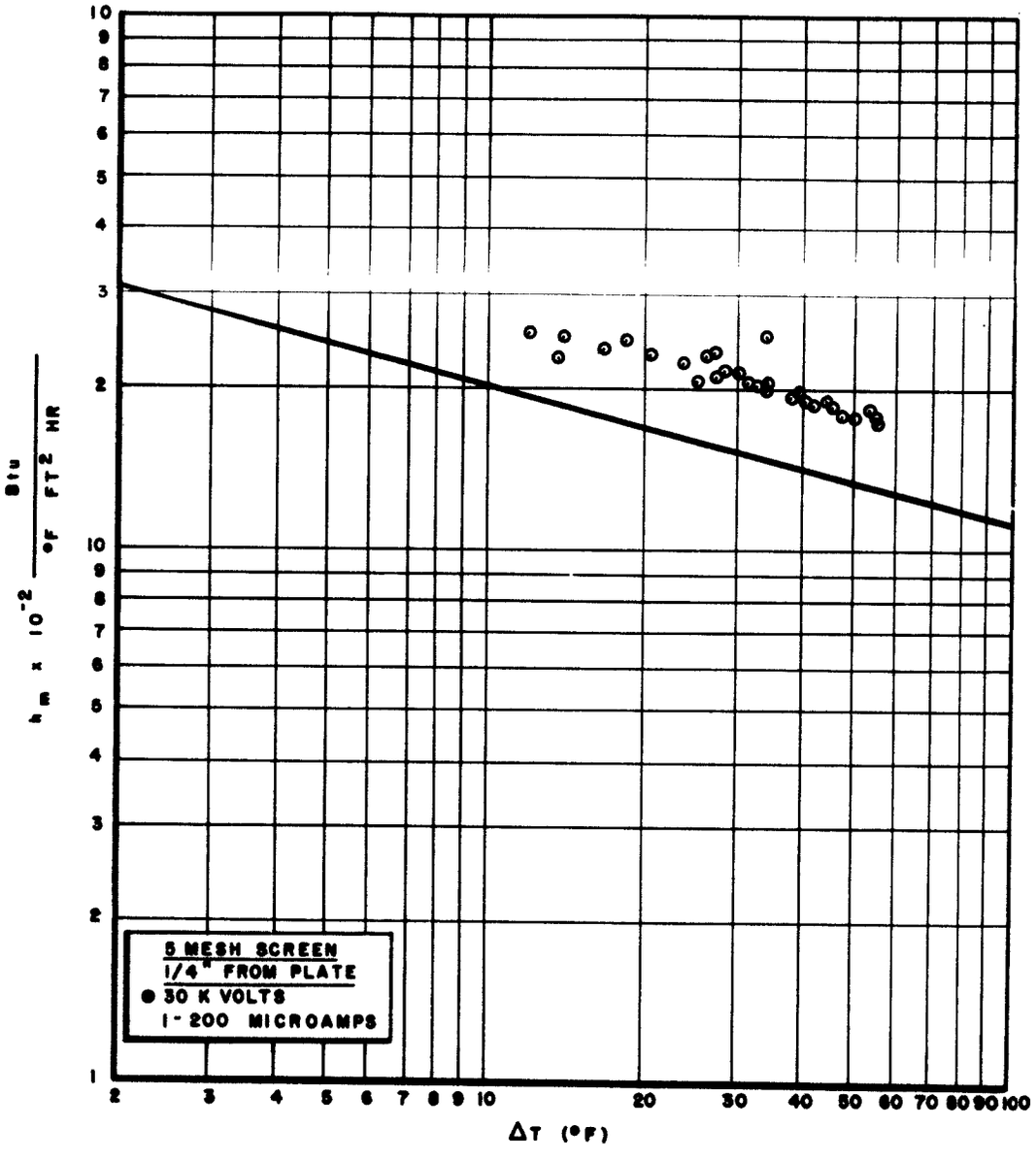

Figure 16. Effects of Localized Electrical Breakdown on Heat Transfer Coefficient

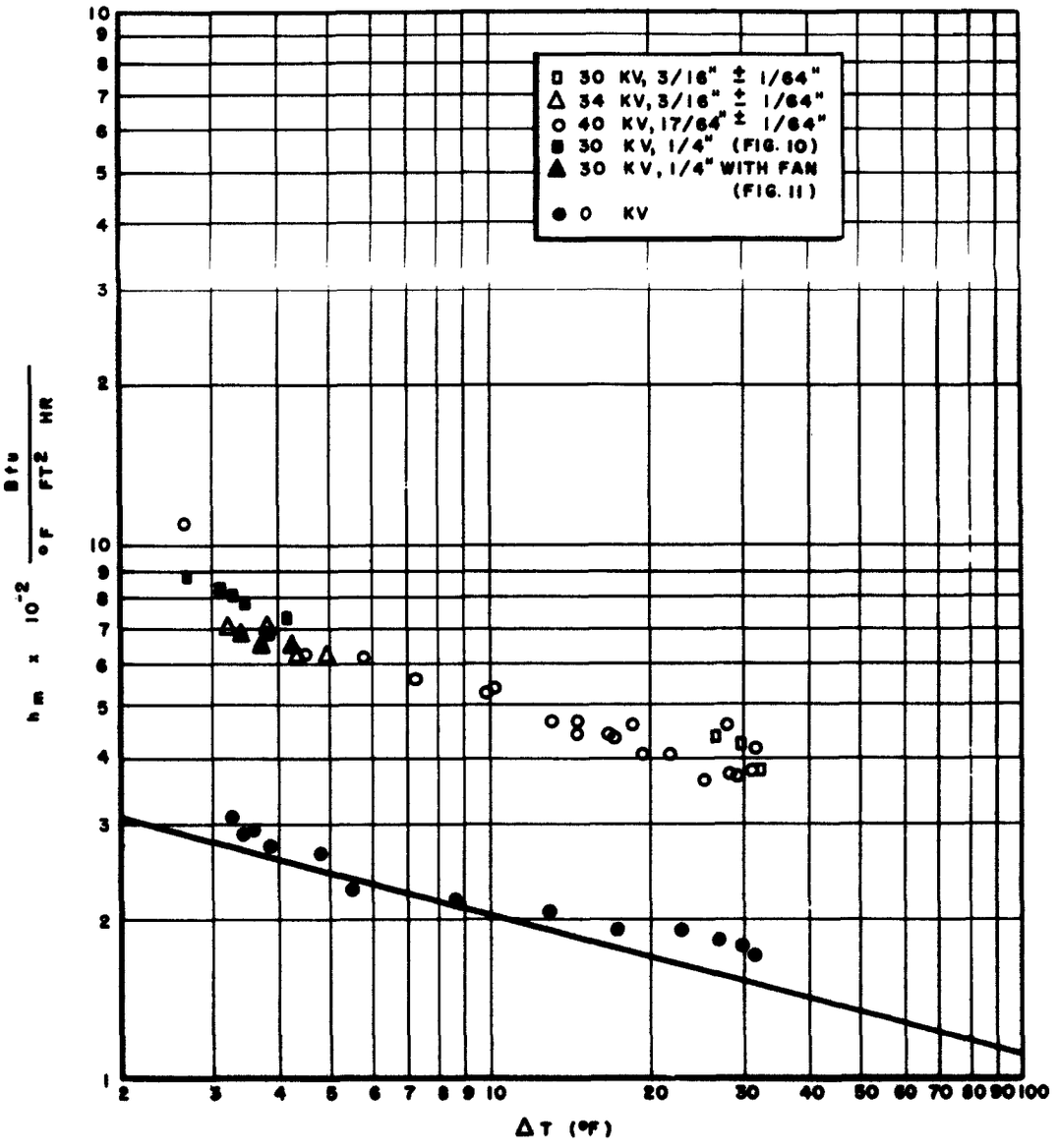

Figure 17. Summary of Values Obtained with 5-Mesh Screen at Wide Range of ΔT

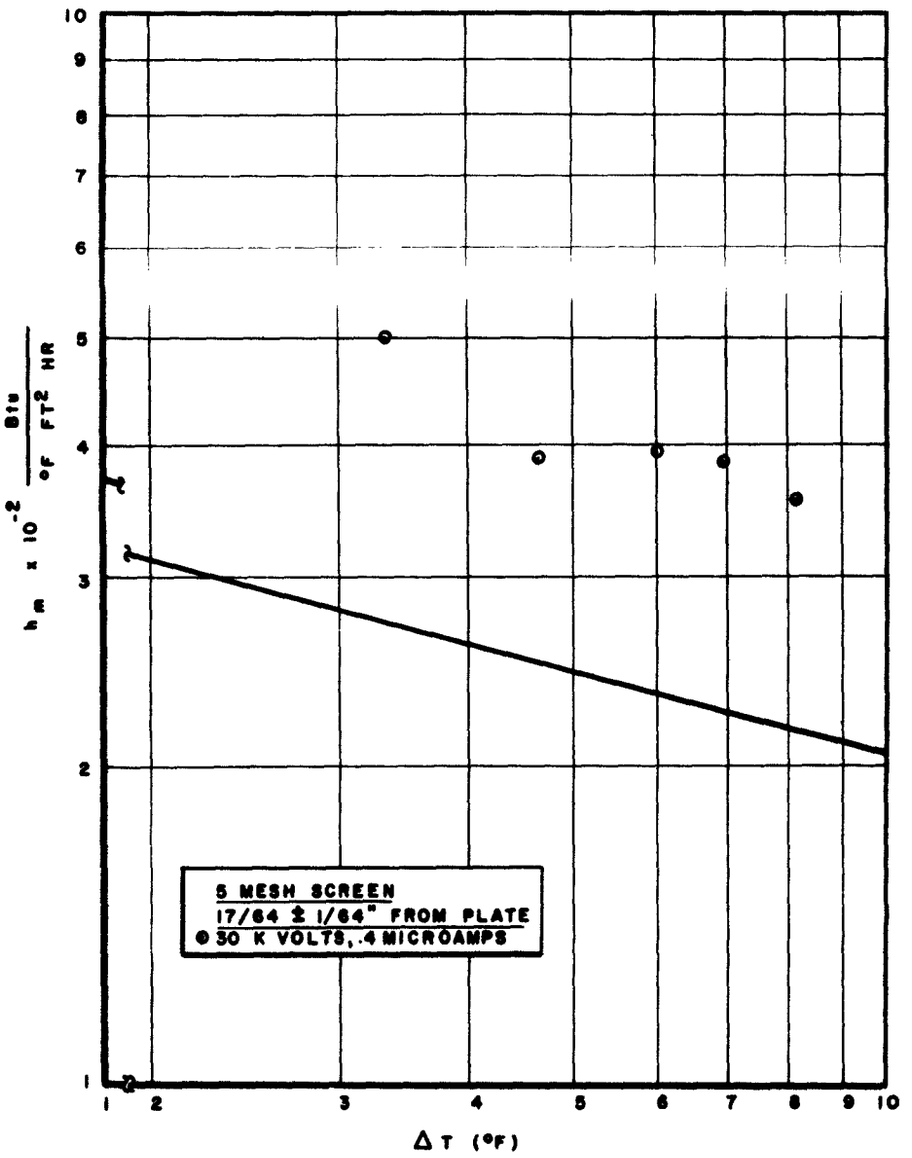

Figure 18. Effects of Using 5-Mesh Screen at 17/64 Inch from Plate

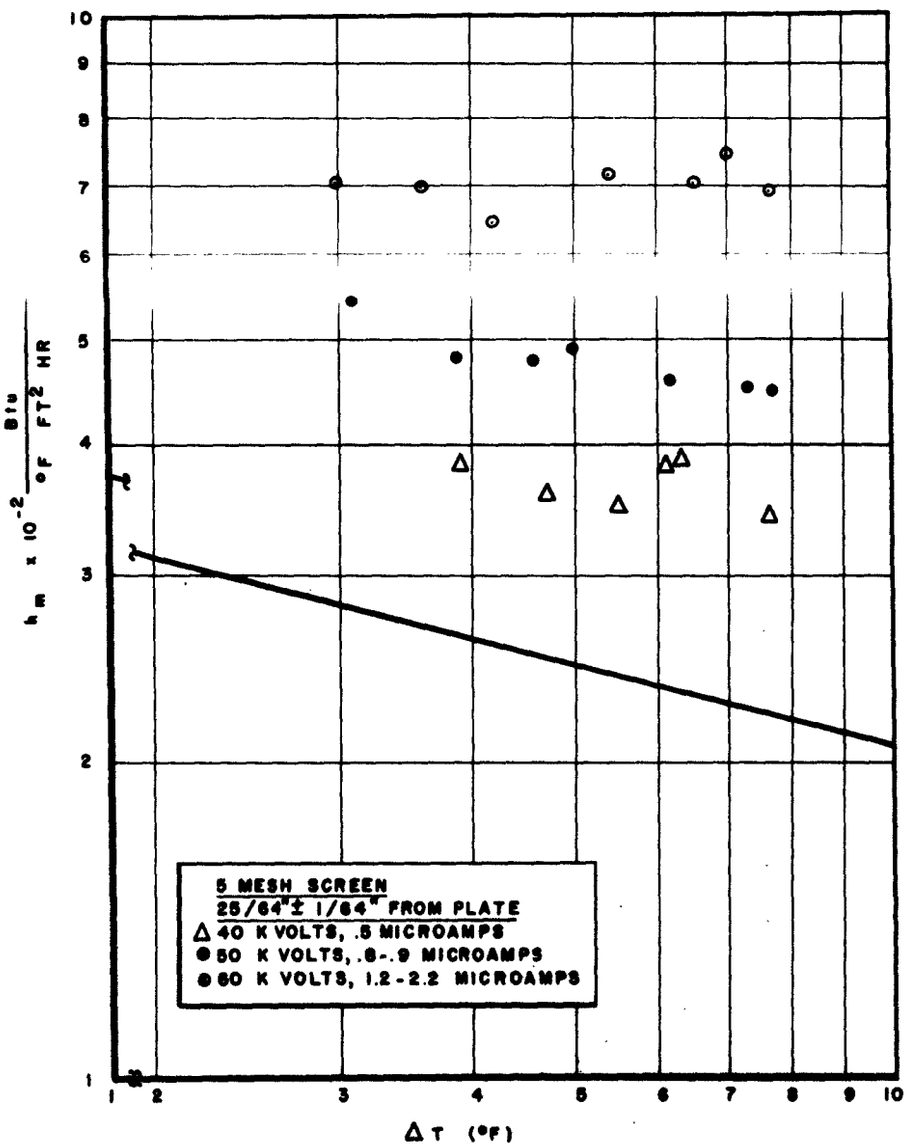

Figure 19. Effects of Using 5-Mesh Screen at 25/64 Inch from Plate

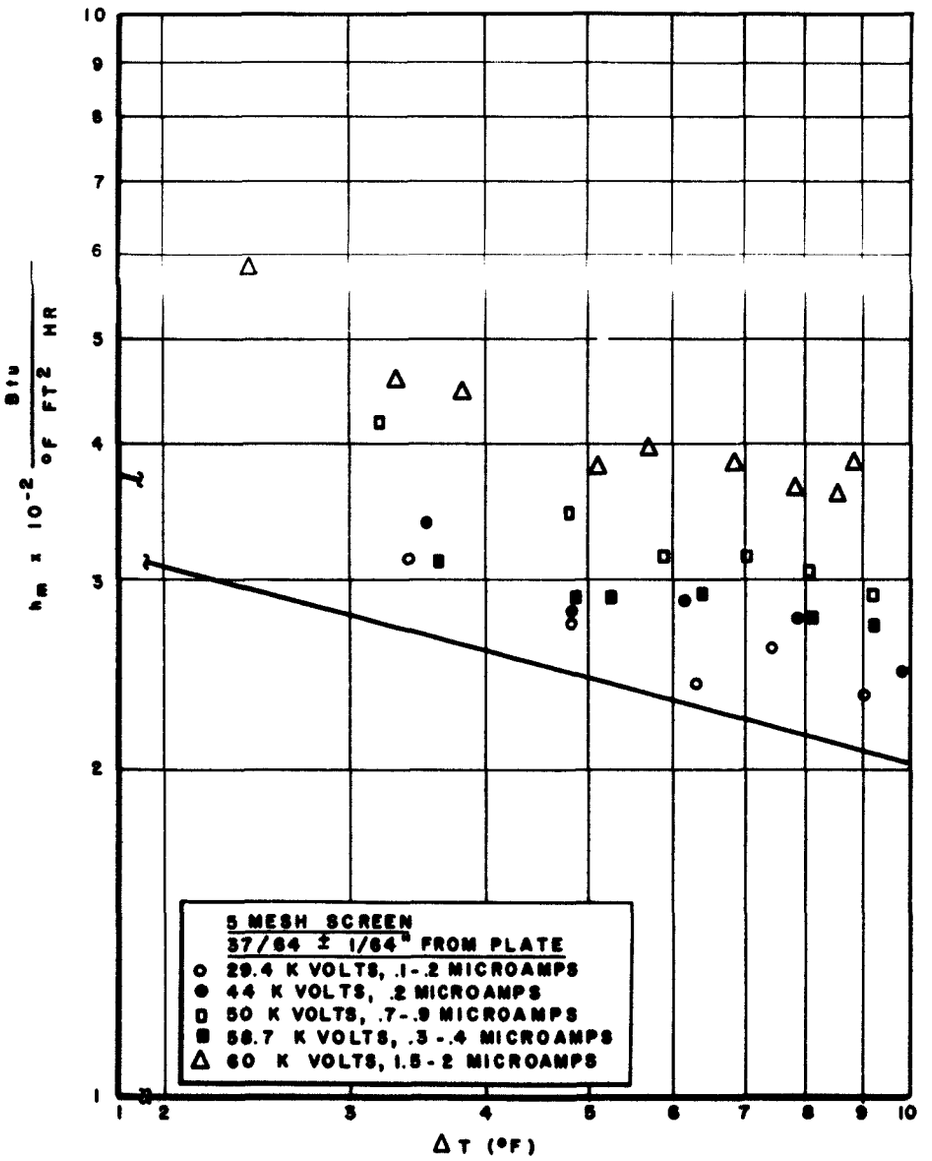

Figure 20. Effects of Using 5-Mesh Screen at 37/64 Inch from Plate

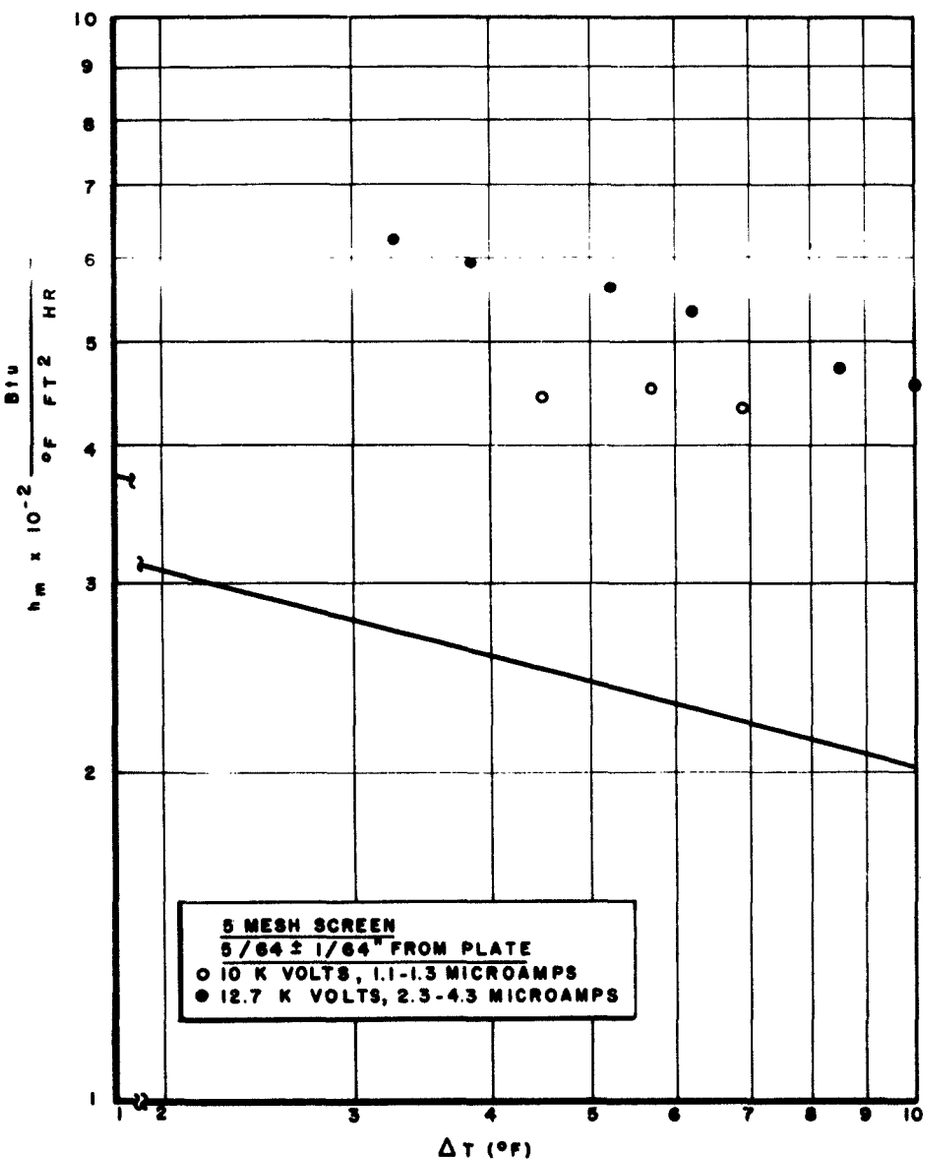

Figure 21. Effects of Using 5-Mesh Screen at 5/64 Inch from Plate

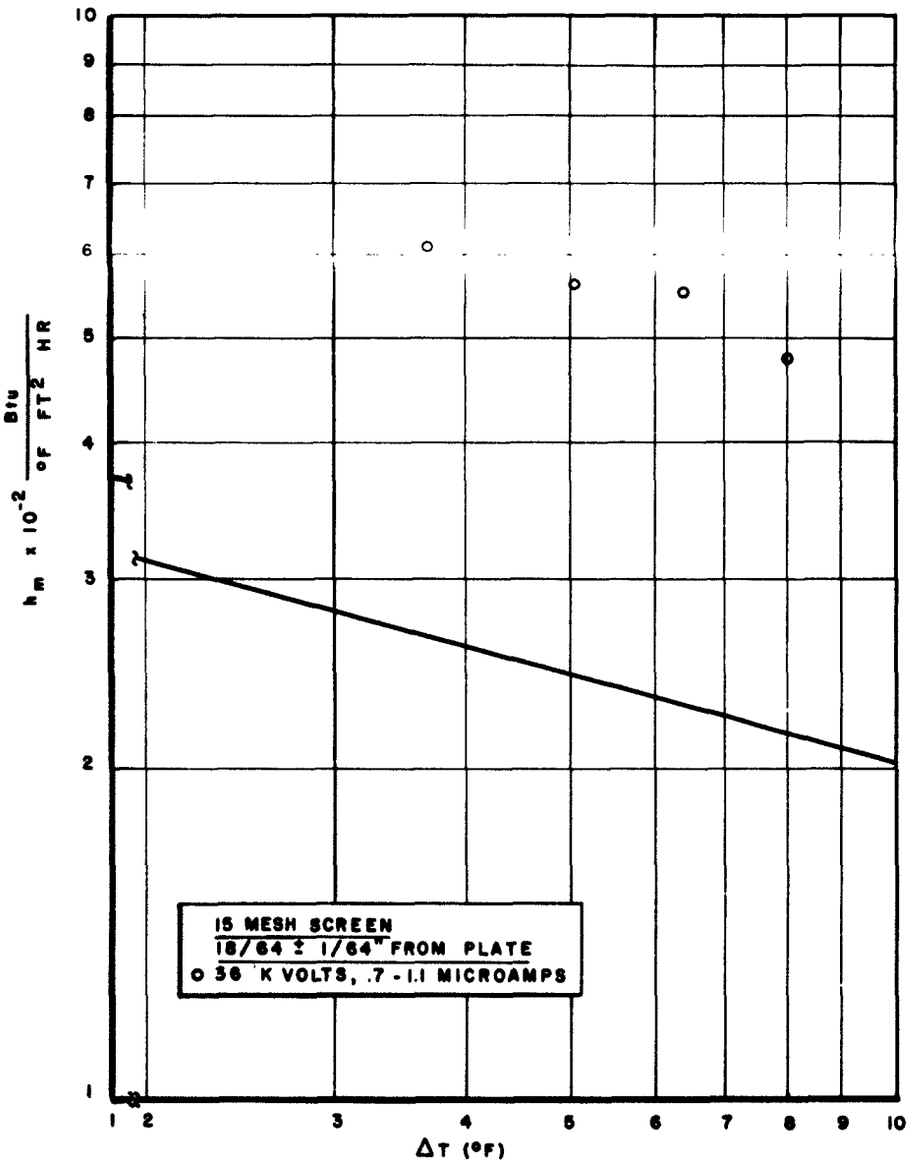

Figure 22. Effects of Using 15-Mesh Screen at 18/64 Inch from Plate

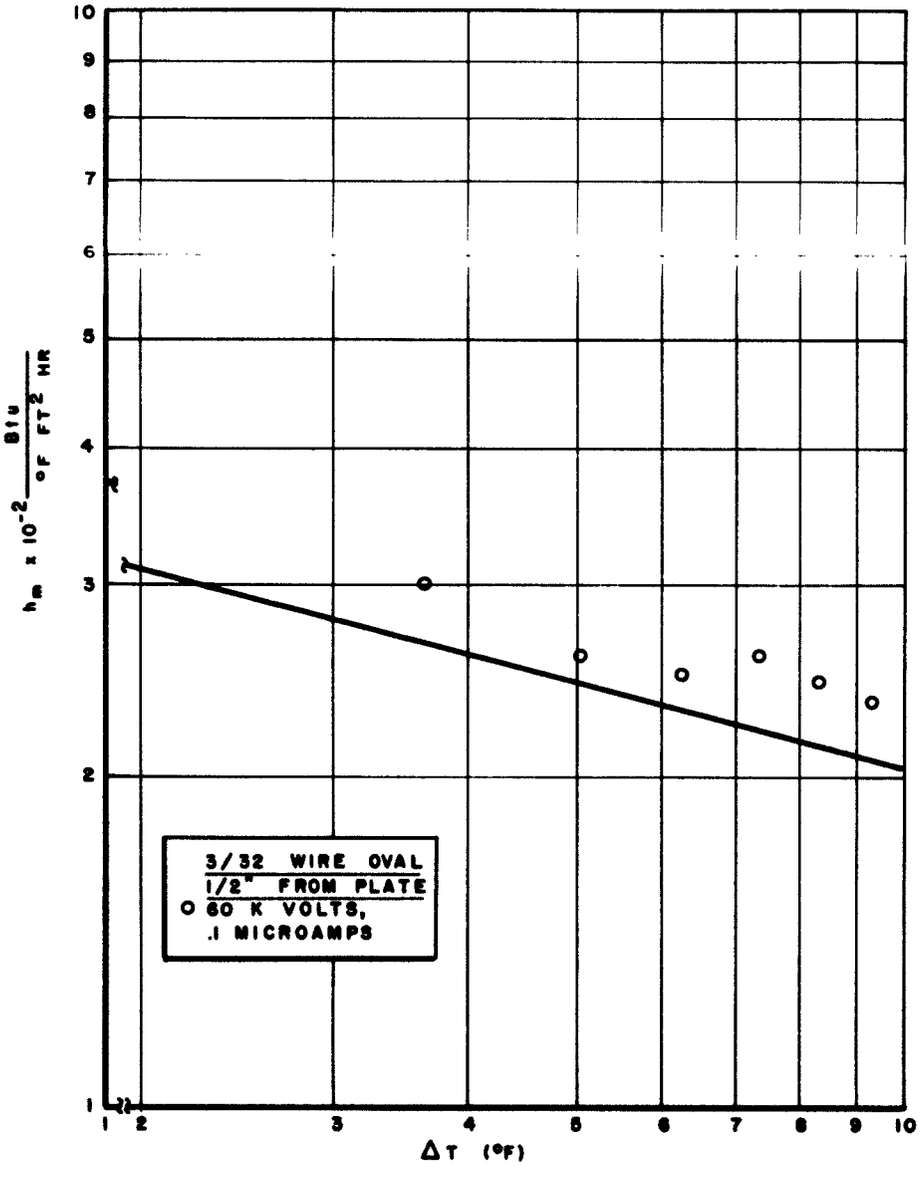

Figure 23. Effects of Using Oval Wire Electrode

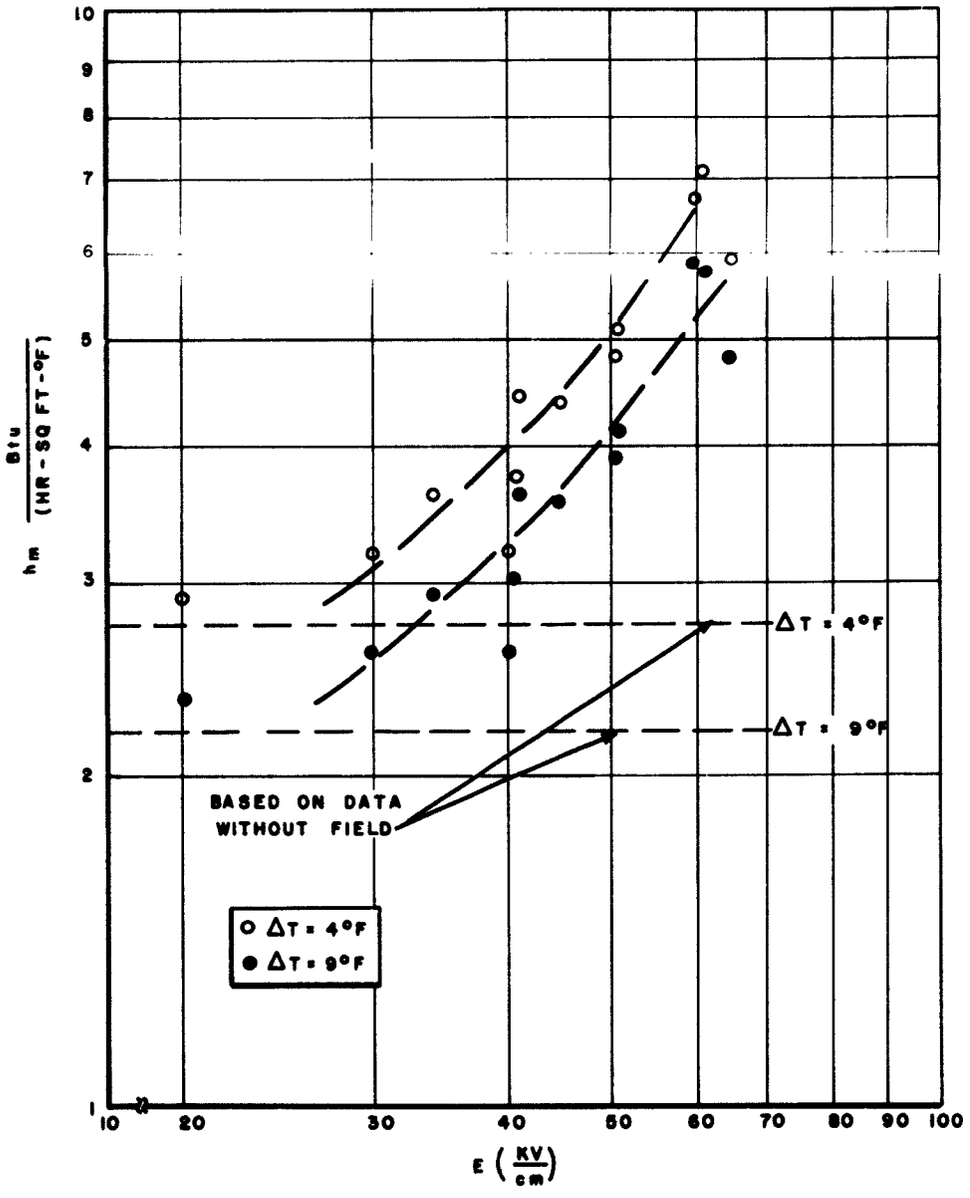

Figure 24. Variation of Heat Transfer Coefficient with Field Strength

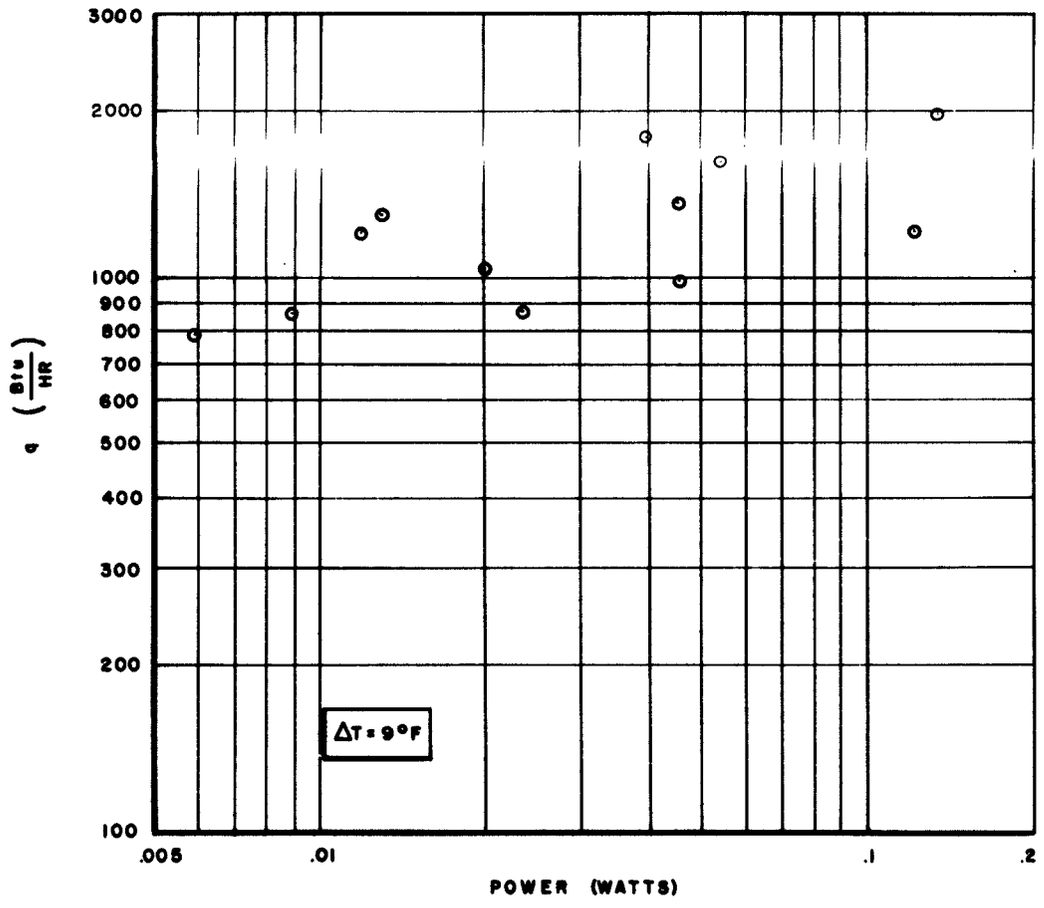

Figure 25. Variation of Heat Transferred (q) with Electrical Power Input to Electrode

ANALYSIS OF TEST RESULTS

The action that took place from an electrostatic field applied with a 5-mesh screen electrode was fascinating and puzzling. Condensate appeared to be pumped off both the condenser and the screen electrode, yet no mechanism exists whereby condensation can occur on the screen. The screen is located in vapor space: it is neither heated nor cooled, nor does the applied field cause any electrical energy to be dissipated in the grid. Consequently, the temperature of the grid must be approximately the same as the temperature of the vapor; in this case, it would appear impossible for the grid to cause any condensation of the vapor. If the Freon should condense on the screen, it would have to give up its latent heat to the grid, and this would cause the grid temperature to rise. Such action would obviously be a violation of the second law of thermodynamics.

An explanation of the phenomenon requires that we consider the effects of the electrical field on the surface of the film. As was stated earlier, two related phenomena are active at the surface of the film due to the applied field: (1) the destabilization of the film, and (2) the pumping off of the liquid. These two actions are explained as follows.

Consider an ideal parallel plate condenser. A layer of conducting liquid covers the inner surface. As an electrical field is applied, an effective charge builds up on the surface of the liquid. Concurrently, an electrostatic pressure is built up within the liquid, which is of the form:

$$P = \frac{1}{2} \epsilon E^2$$

At some value of field strength, the charge repulsion at the surface approximates the value of the surface tension, which results in a potential instability of the surface. This condition has been studied many times. The Rayleigh theory (Ref. 6), which applies to the case of a charged droplet or charged layer on a cylinder, indicates that only certain droplet sizes are permissible for a given field strength. At higher values of field strength, as Lawson, Von Ohain, and Wattendorf indicated in Reference 7, stable droplets can be of very small size, so small, in some cases, as to be less than the wavelength of visible light.

Based upon the above consideration, the following mechanism is postulated as being active during condensation of vapor with an applied field. As the field strength increases, a level of electrostatic charge is reached at which the film surface becomes unstable. At the outset, it can be anticipated that this instability would appear as a waviness, then as peaked waves, and then as sharp points of liquid. As indicated in studies of electrical spray phenomena (Ref. 8), thin jets of liquid should be sprayed from the surface. These jets should break up into very fine droplets, the size of which would be determined by the Rayleigh limit. These drops are highly charged, and therefore accelerate toward the oppositely charged electrode in exactly the same manner as the charged colloids in ion propulsion studies (Ref. 9). In this case, the droplets are attracted toward the screen electrode and collect there. The same pumping action can occur from the grid toward the plate, but the net result is a substantial pumping of the liquid away from the plate.

The above action could result in a thinning of the film of liquid on the condenser and, thus, could provide a corresponding increase in heat transfer coefficient. The experimental observation that no spray from the plate itself (only jets of fluid moving downwardly from the bottom of the plate) was visible during the tests may possibly be explained by the Rayleigh limit on droplet size. At very high values of field strength, the droplets

may simply be too small to be seen, since they may be smaller than the wavelength of light.

Analysis of the results of the various tests indicates the following:

1. The action of corona discharge mechanisms led to only small improvements in heat transfer. When the net power required to accomplish the corona charging action is considered, the net gain at higher values of current is so small as to be unusable.

2. The electrostatic field produced by the oval 3/32-inch-diameter-wire electrode did not improve the heat transfer coefficient.

3. Fan-induced forced convection and turbulence in the vapor did not affect the heat transfer coefficient with or without an electrostatic field.

4. Using a flat aluminum plate electrode resulted in increases in the heat transfer coefficient, but the increases were less than those obtained with the screen electrodes.

5. Using the 5-mesh screen as the electrode produced increases in heat transfer coefficient that were approximately triple those obtained without an electrostatic field. Values were repeatable and are valid over a broad range of temperature difference. The data indicate that the phenomena become active at a definite cut-in voltage, as had been anticipated from a preliminary consideration of the mechanisms involved in the stability of the film.

6. Using the 15-mesh screen as the electrode produced large increases in heat transfer coefficient, also, but the gains were not as great as for the 5-mesh screen. We believe that the difference in value is due to the difference in size of the wire in the two screens. The fine wire of the 15-mesh screen would suffer a localized corona discharge at a lower value of field strength than the heavier wire of the 5-mesh screen. The 15-mesh screen, therefore, could not produce as high values of field strength.

CONCLUSIONS AND RECOMMENDATIONS

The results of this exploratory program show that electrostatic effects can affect the film of condensate on a condenser to improve the heat transfer coefficient. The improvements in heat transfer coefficient obtained in tests using a 5-mesh screen electrode far exceeded the initial goals established for the program. The threefold increase obtained with small expenditures of electrical power indicates that this technique holds considerable promise for improving the design of condensing heat exchangers.

Although this initial exploratory work was conducted with Freon-113, the principle should be equally applicable to other fluids such as liquid air. In applying the technique to other liquids, however, we must recognize that the characteristics of the liquid (such as electrical conductivity, surface tension, dielectric constant, and breakdown strength) could markedly affect the gains to be achieved.

The gains experienced in this test program are believed to be of sufficient magnitude to warrant further investigation. Logical extensions of this work would include developing a comprehensive analytical theory of the action by the electrostatic field and designing and testing a typical heat exchanger configuration using the electrostatic field technique. Effects on condensation collecting on the exterior of tube bundles and on condensation from superheated vapor are other areas that should be considered.

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APPENDIX

TEST APPARATUS, ELECTRODES, AND PROCEDURES

TEST APPARATUS

The test apparatus used in this study, in general, consisted of two parts: the boiler, which was used to vaporize the liquid; and the condenser, which was used to condense the vapor. The configuration of the apparatus was shown in Figure 2.

In this configuration, the boiler consisted of a plexiglas tank with heaters installed at the bottom. Enough fluid was poured into the tank to cover the heaters. A voltmeter and an ammeter were attached to the heaters to measure the electrical power used to vaporize the liquid. A pressure gage was installed on the tank to permit vapor pressure to be maintained at a uniform level. Freon-113 was used as the working fluid in all of these tests.

The condenser consisted of a copper plate installed in a hole cut in one wall of the tank, as shown in Figure 26. The plate was 1/2-inch-thick sheet copper and had a condensing surface measuring 6 by 9 inches. Copper tubing 1/4 inch in diameter was soldered to the back of the plate, as shown in the back view, Figure 26. Coolant was pumped through this tubing during the tests to cool the plate.

Freon-113 (trichlorotriflourethane) was used as the coolant for the condenser because of its low electrical conductivity. The Freon flowed through a closed circuit consisting of a pump, a heat exchanger, and a hold-up tank, as shown in Figure 27. Flow rate was measured with a 3/16-inch potter meter. Thermocouples were installed in the inlet and return lines to measure temperatures (T_i and T_R). These measurements were used to determine temperature rise of the coolant and thus the heat conducted from the copper plate.

The heat exchanger was used to regulate the temperature of the coolant. Water was used in the heat exchanger to absorb heat from the coolant for most of the tests. A photograph of the test apparatus when water was used is shown in Figure 28. When the apparatus was revised to produce lower temperatures, a Stoddard solvent-dry ice bath was used in the heat exchanger, as shown in Figure 29.

Tygon plastic hose was used to connect the copper tubing on the back of the condenser to the rest of the flow circuit, as shown in Figure 30. This tubing insulated the copper plate electrically from its surroundings. The wooden box around the tubing and back of the plate was filled with Perlite insulation to insulate the plate thermally from the coolant lines.

Nine iron-constantan thermocouples were inserted through the back of the plate to within 1/32 inch of its front to measure the temperature of the condensing surface. These thermocouples were insulated electrically from the plate by a small amount of insulation. The positions of these thermocouples are shown in Figure 31. The temperature of the vapor 1-1/2 inches in front of the condensing plate was measured by three thermometers installed at the vertical centerline but at three different heights which corresponded to the placement of the thermocouples, as shown in Figure 31.

The thermocouples were calibrated against the thermometers after they were installed in the condensing plate. This calibration was accomplished by filling the entire tank with Freon-113 and mixing well to obtain a uniform temperature throughout the tank. Readings on both thermometers and thermocouples were made at temperatures between 95 and 113°F.

ELECTRODES

Several types of electrodes were used in these tests to determine the effects of different types of electrostatic actions. These electrodes are shown in Figure 32. The single vertical, single horizontal, and grid of wires were made of 0.004-inch-diameter wire, and were used to determine the effects of corona current and corona wind. The oval electrode was fabricated from 3/32-inch-diameter rod. The aluminum plate electrode was used to test the parallel-plate geometry of electrostatic field. The 5-mesh and 15-mesh screen electrodes were used to test parallel-plate geometry with a less restricted vapor flow path than possible with the flat aluminum plate. The vertical and horizontal wire electrodes are shown installed in the tank in Figure 33. The screen electrode can be seen installed in Figure 26.

A film of condensate built up on the fine wire electrodes when current was applied during tests. This film is considered to be related to the non-uniform field body force (action 3 of electrostatic effects under Preliminary Considerations). Since this layer of condensate prevented the corona discharge, heat was applied to the wire electrodes to vaporize the condensate. The wiring diagram in Figure 34, shows the heating system used with the wire electrodes. The battery in the circuit was removed when the other electrodes were used.

TEST PROCEDURES

At the beginning of a test, the Freon in the tank was heated to the boiling point with the tank vented to allow air to escape. When the air was displaced, the tank was closed and the Freon was vaporized at the rate necessary to maintain a pressure of 1 inch of water above ambient pressure. Vaporization was controlled by adjusting power to the heater with a variac.

The condenser was cooled by circulating the coolant through the tubes on the back of the plate. The temperature of the condenser was controlled by adjusting the temperature and flow rate of the coolant. Data were recorded when the temperature of the coolant had been constant for a period of 5 minutes and remained constant during the time that a complete set of readings was taken. Values for heat absorbed by the coolant and the difference between the average plate temperature and average vapor temperature were used to calculate the heat transfer coefficient.

Tests were conducted with the various electrodes under varying conditions. Electrodes were installed at a distance of between 5/64 and 2 inches from the front of the condenser, and the voltage applied to the electrodes was varied between 0 and 60 KV.

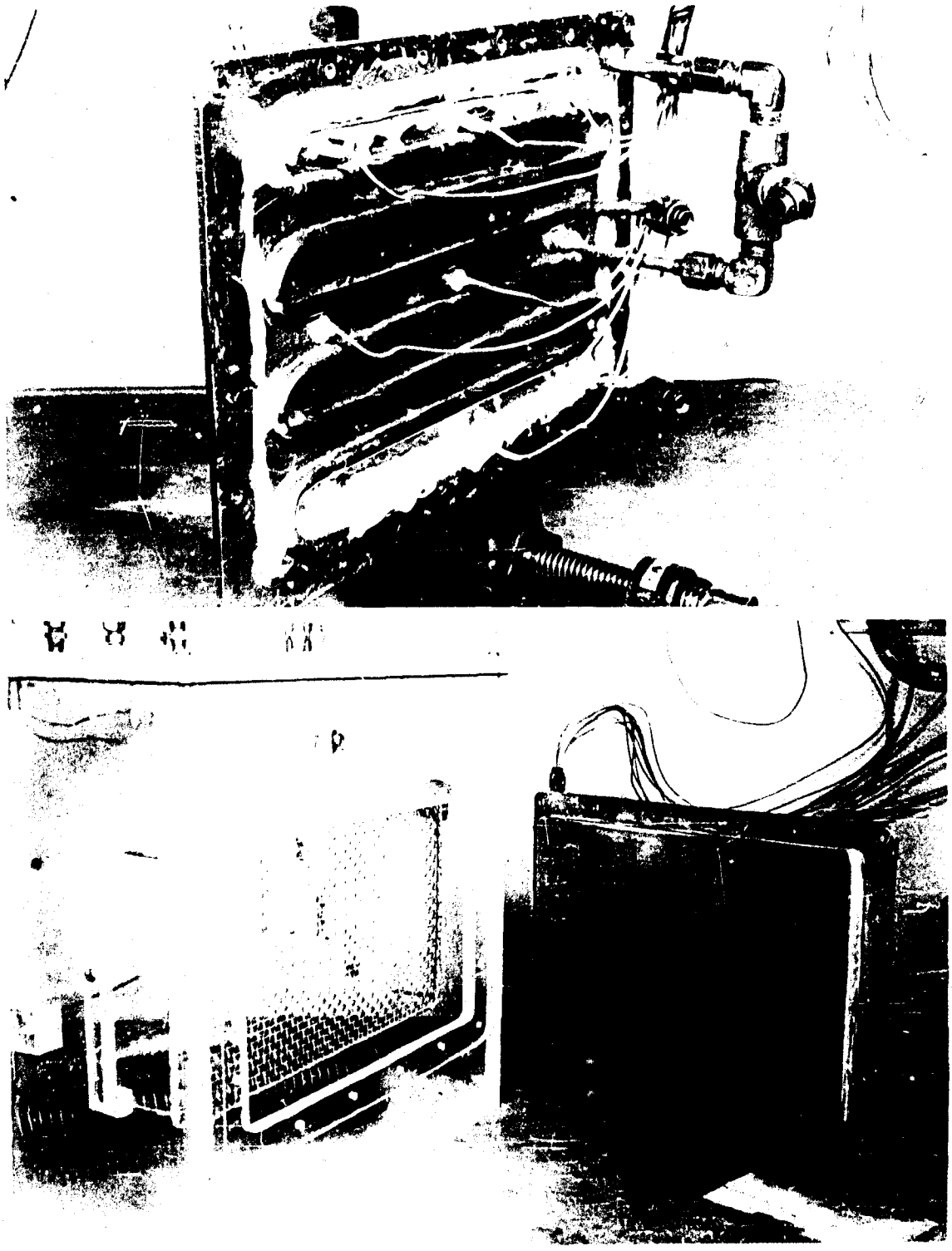

Figure 26. Condenser Plate

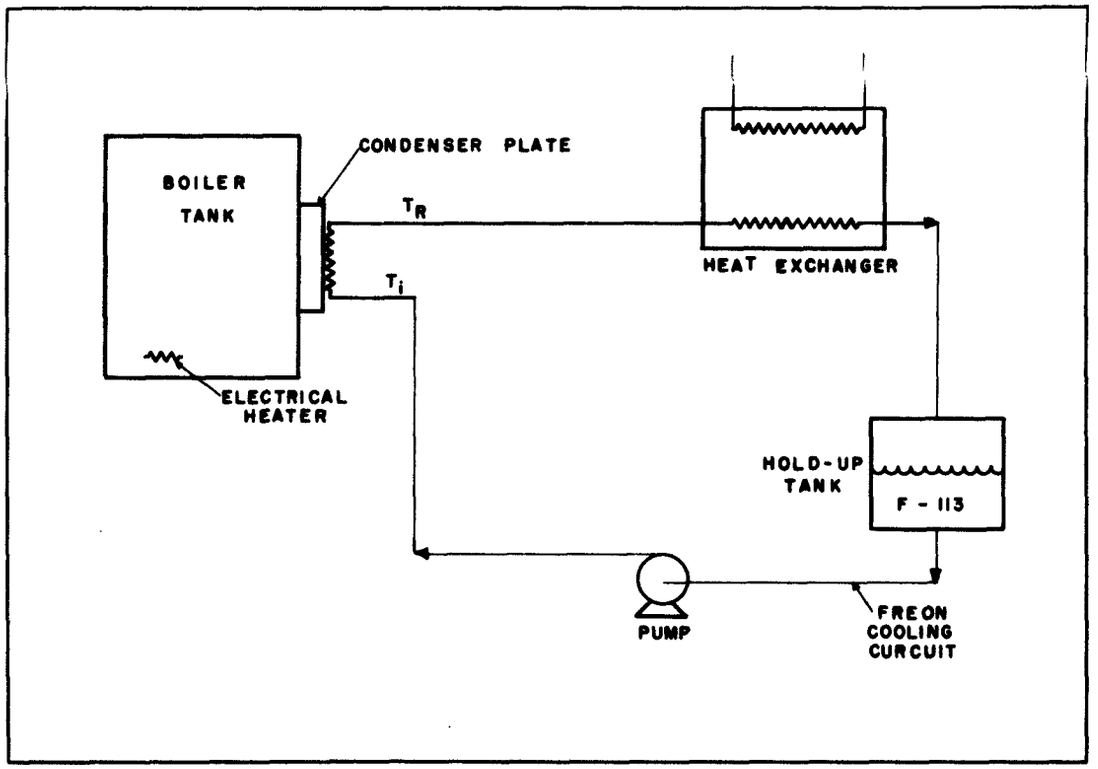

Figure 27. Schematic of Cooling Circuit

Figure 25. Photograph of Initial Test Apparatus

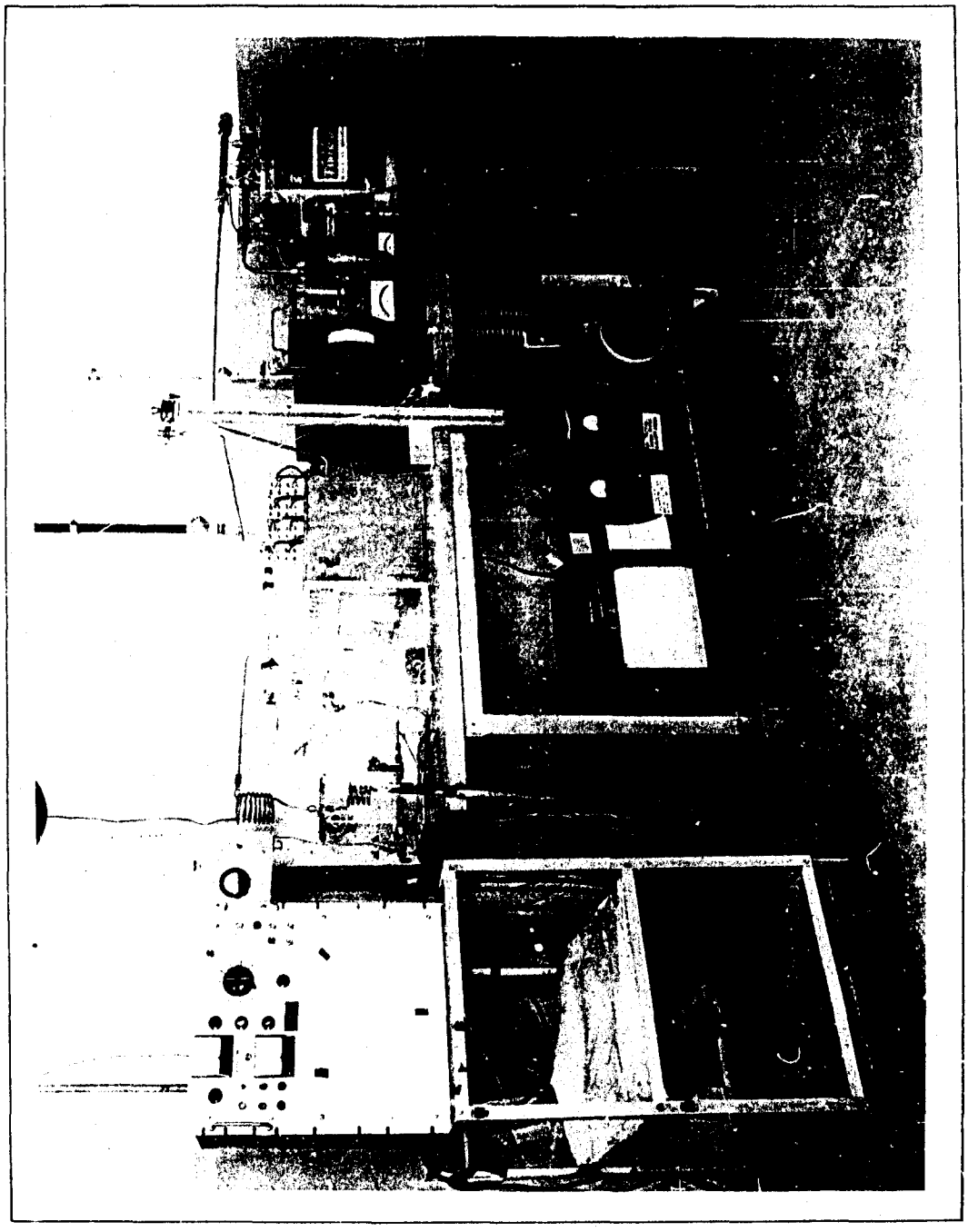

Figure 2-. Photograph of Low Temperature Test Specimen

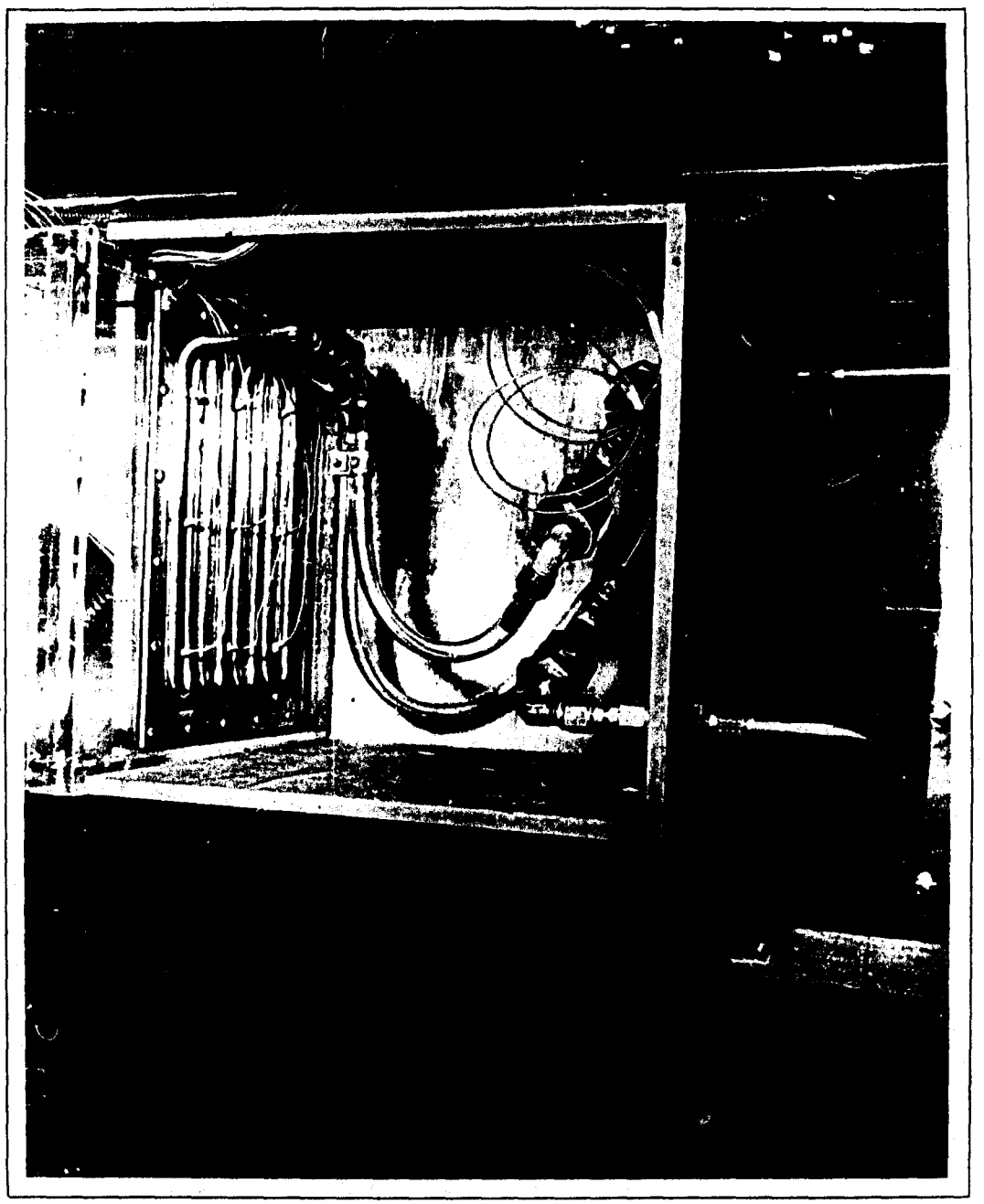

Figure 30. Connections from Plate to Flow Circuit

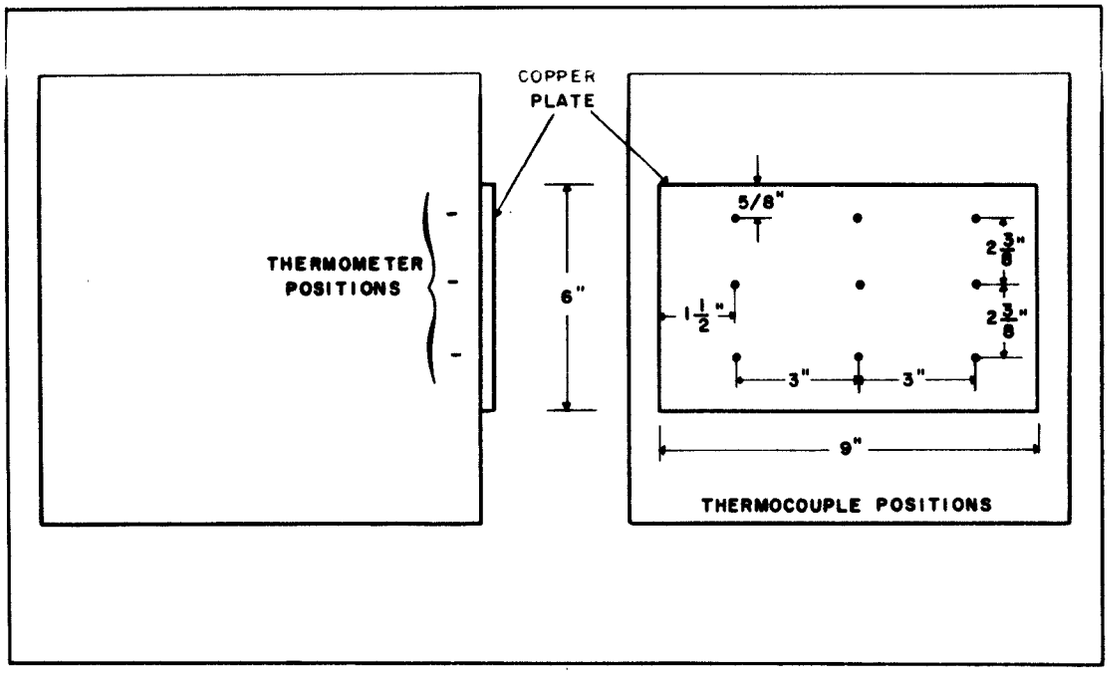

Figure 31. Thermocouple and Thermometer Positions

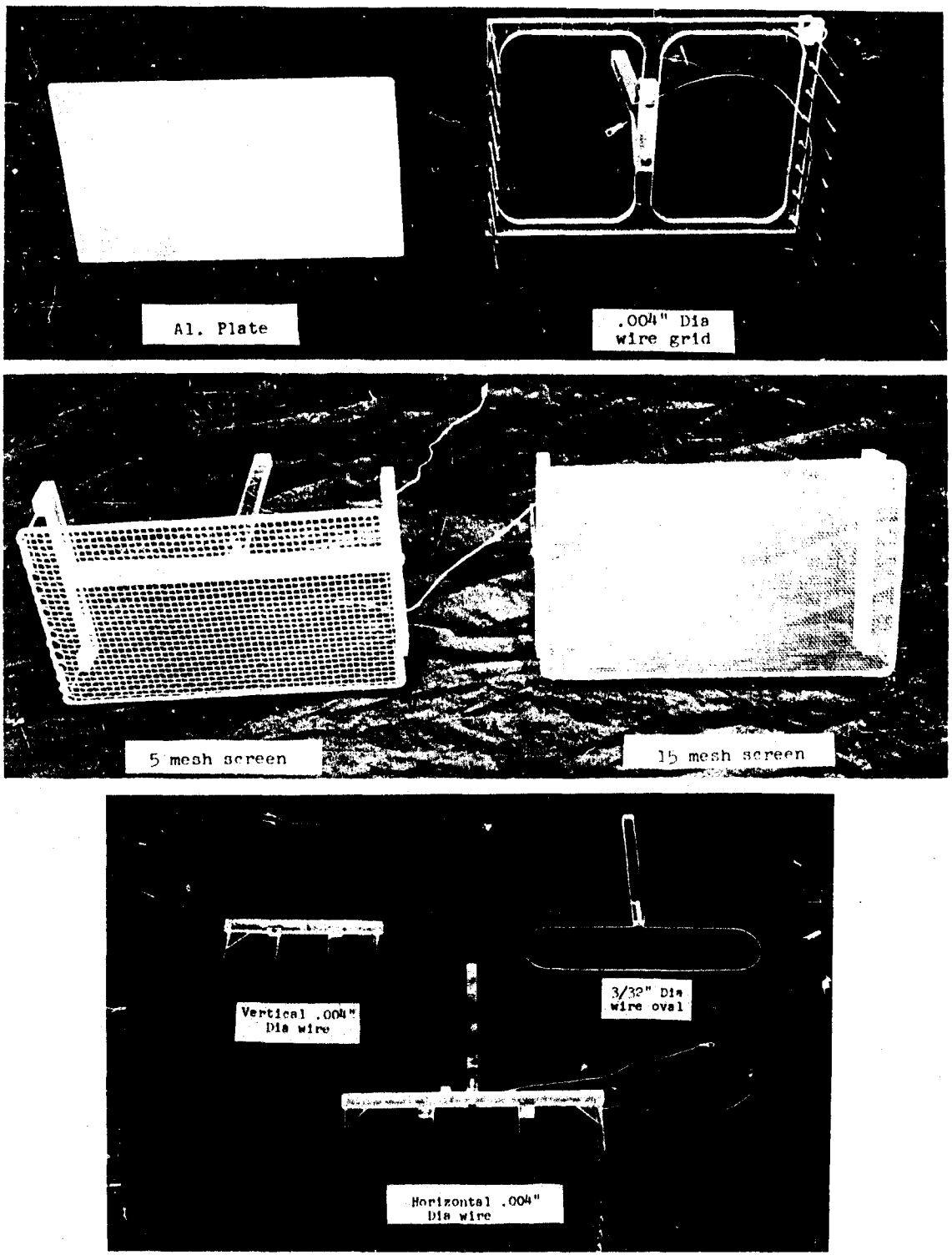

Figure 32. Electrodes

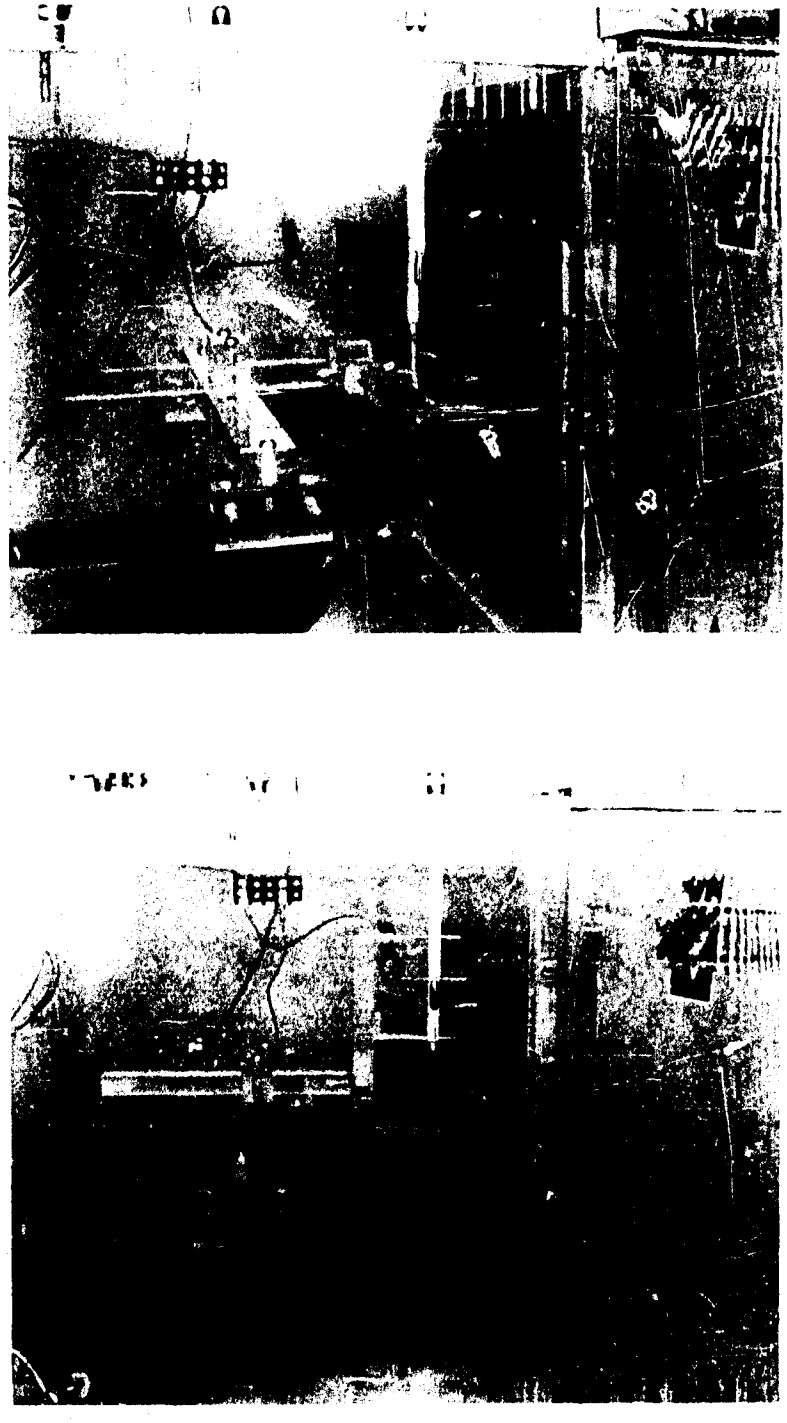

Figure 33. Single Wire Electrodes Installed in Tank

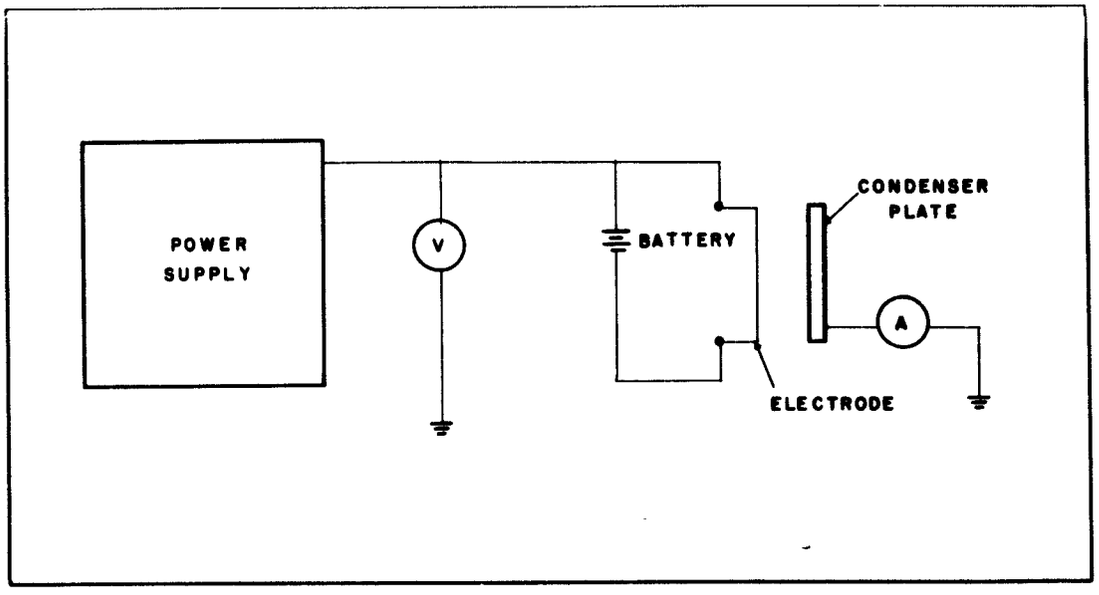

Figure 34. Electrical Wiring Diagram